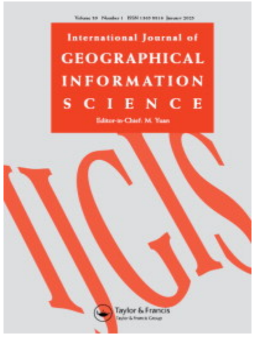

Taylor & Francis
Taylor & Francis Group

International Journal of Geographical Information Science

ISSN: 1365-8816 (Print) 1362-3087 (Online) Journal homepage: www.tandfonline.com/journals/tgis20

A research agenda for GIScience in a time of disruptions

Trisalyn Nelson, Amy E. Frazier, Peter Kedron, Somayeh Dodge, Bo Zhao, Michael Goodchild, Alan Murray, Sarah Battersby, Lauren Bennett, Justine I. Blanford, Carmen Cabrera-Arnau, Christophe Claramunt, Rachel Franklin, Joseph Holler, Caglar Koylu, Angela Lee, Steven Manson, Grant McKenzie, Harvey Miller, Taylor Oshan, Sergio Rey, Francisco Rowe, Seda Şalap-Ayça, Eric Shook, Seth Spielman, Wenfei Xu & John Wilson

To cite this article: Trisalyn Nelson, Amy E. Frazier, Peter Kedron, Somayeh Dodge, Bo Zhao, Michael Goodchild, Alan Murray, Sarah Battersby, Lauren Bennett, Justine I. Blanford, Carmen Cabrera-Arnau, Christophe Claramunt, Rachel Franklin, Joseph Holler, Caglar Koylu, Angela Lee, Steven Manson, Grant McKenzie, Harvey Miller, Taylor Oshan, Sergio Rey, Francisco Rowe, Seda Şalap-Ayça, Eric Shook, Seth Spielman, Wenfei Xu & John Wilson (2025) A research agenda for GIScience in a time of disruptions, International Journal of Geographical Information Science, 39:1, 1-24, DOI: 10.1080/13658816.2024.2405191

To link to this article: https://doi.org/10.1080/13658816.2024.2405191

INTERNATIONAL JOURNAL OF GEOGRAPHICAL INFORMATION SCIENCE
2025, VOL. 39, NO. 1, 1–24
https://doi.org/10.1080/13658816.2024.2405191

FORESIGHT PAPER

A research agenda for GIScience in a time of disruptions

Trisalyn Nelson[a], Amy E. Frazier[a], Peter Kedron[a], Somayeh Dodge[a], Bo Zhao[b], Michael Goodchild[a], Alan Murray[a], Sarah Battersby[c], Lauren Bennett[c], Justine I. Blanford[d], Carmen Cabrera-Arnau[e], Christophe Claramunt[f], Rachel Franklin[g], Joseph Holler[h], Caglar Koylu[i], Angela Lee[c], Steven Manson[j], Grant McKenzie[k], Harvey Miller[l], Taylor Oshan[m], Sergio Rey[n], Francisco Rowe[e], Seda Şalap-Ayça[o], Eric Shook[j], Seth Spielman[p], Wenfei Xu[q] and John Wilson[r]

[a]Department of Geography, University of California Santa Barbara, CA, USA; [b]Department of Geography, University of Washington, Seattle, WA, USA; [c]ESRI, Redlands, CA, USA; [d]Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, Enschede, the Netherlands; [e]Department of Geography and Planning, University of Liverpool, United Kingdom; [f]Naval Academy Research Institute, Lanvéoc, France; [g]School of Geography, Politics and Sociology, Newcastle University, Newcastle, United Kingdom; [h]Department of Geography, Middlebury College, Middlebury, VT, USA; [i]Department of Geographical and Sustainability Sciences, University of Iowa, Iowa City, IA, USA; [j]Department of Geography, Environment and Society, University of Minnesota, Minneapolis, MN, USA; [k]Department of Geography, McGill University, Montreal, Canada; [l]Department of Geography, Ohio State University, Columbus, OH, USA; [m]Department of Geographical Sciences, University of Maryland, College Park, MD, USA; [n]Department of Geography, San Diego State University, San Diego, CA, USA; [o]Department of Earth, Environmental, and Planetary Sciences, Institute at Brown for Environment and Society, Brown University, Providence, CA, USA; [p]Microsoft, Inc, Boulder, CO, USA; [q]Department of City and Regional Planning, Cornell University, NY, USA; [r]Spatial Sciences Institute, University of Southern California, CA, USA

ABSTRACT
Social issues, AI, and climate change are just a few of the disruptive focuses impacting science. The field of GIScience is well positioned to respond to accelerating disruptions due to the interdisciplinary nature of the field and the ability of GIScience approaches to be used in support of decision-making. This manuscript aims to start a conversation that will establish a research agenda for GIScience in an age of disruptions. We outline three guiding principles: (1) focusing on the relevance and real-world impact of research, (2) adopting systems-based thinking and contextual approaches and (3) emphasizing inclusive practices. We then outline prioritized research areas organized by what topics are important focal areas (Data and Infrastructure, Artificial Intelligence, and Causality and Generalizability), and what approaches to science we should be attentive to (Impactful Open Science, Collaborative and Convergent Science, and through Diverse Participation and Partnerships). We conclude with a call to increase impact by balancing slow science with practical and policy-oriented research. We also recognize that while broad adoption of spatial approaches is a signal of GIScience's success, we should continue to work together to advance core knowledge centered on spatial thinking and approaches.

ARTICLE HISTORY
Received 10 June 2024
Accepted 11 September 2024

KEYWORDS
Modern GIScience; research agenda; GeoAI; DEI; open science

CONTACT Trisalyn Nelson trisalyn@ucsb.edu

Introduction

Disruptive changes in society and the environment dramatically alter the functioning of systems, which can challenge existing understanding, push scientific inquiry in new directions, and alter research practices. Almost all scientific disciplines and research environments are experiencing unprecedented disruption. Some of these disruptions stem from shifts in society, such as those driven by the COVID-19 pandemic, while others have emerged from technological developments. Examples of the latter include the explosive growth of generative artificial intelligence (AI) and the rapid advancement of high-performance computing. Combined with political divisiveness, these technologies can be manipulated to produce misinformation and cause social upheaval. Still other disruptions reflect shifts in values, such as a sharpening focus on equity and inclusion, or environmental degradation, like the dual climate change and biodiversity crises threatening over a million species with extinction (Tollefson 2019). Individually and collectively, these disruptions have the potential to fundamentally alter life on earth.

While disruptions change the practice of science, there is a more fundamental reformation occurring in the way in which scientific problems are approached. Data-intensive scientific discovery has shifted which products researchers prioritize and pursue. Expansion of cyberinfrastructure ecosystems and algorithmic advances in AI have created new modes of discovery that challenge long-standing practices and open the possibility of widespread social reorganization. At the same time, climate change and ongoing advances in communication continue to alter the physical and human geography of the planet, as well as human-environment interactions, evolving the theoretical and empirical foundations on which our discipline is rooted. Disruptions also raise ethical questions about science practices and bring into focus structural barriers to equity and participation in science that require revisions to how research and education are conducted (Nelson *et al.* 2022).

All signs suggest that these major disruptions to science will continue. As such, it is judicious to pause and consider how GIScience should respond to these disruptions and what role GIScientists can play in leading the blending of science and technology while also helping to avert negative consequences that may stem from these disruptions. At its core, GIScience has two aims: first, to discover new knowledge about the geographic world, and second, to use GIS to discover new knowledge in substantive application. Through these aims, GIScientists have built a legacy of informed decision-making related to physical and human environments while also evolving with other disciplinary contexts. Disruptions provide an opportunity to examine how GIScientists can lead the discovery of new geographic knowledge while also asking what those same researchers can learn from these disruptions about our own discipline.

Here, we argue that it is essential for GIScientists to respond to today's disruptions collectively. Our field sits at the intersection of rapidly changing technology and society and has a legacy of providing information for informed decision-making related to physical and human environments. Perhaps every generation of scholars may claim their challenges are the most significant, and their problems are the biggest. We posit that the scale of today's challenges is truly global and will benefit from a coordinated scientific response. Therefore, this paper aims to start establishing a research agenda for GIScience in an age of disruptions.

Many of the points raised below arose during discussions at a specialist meeting held in Santa Barbara, California, on December 8-9, 2023 where 25 GIScientists across academia and industry came together to discuss ideas on how the field should be positioning itself amid disruptions to science. An open call was issued for participation, and the organizing committee made selections with the intention of ensuring diverse participation across academia and industry, career stages, continents, institutional missions, gender and race. We acknowledge that GIScience still has work to do in broadening diverse participation, especially across racial groups. To that end, we begin by discussing common themes that arose from the meeting, which provide a framework for principles that could guide a research agenda for modern GIScience. Following this, we then outline priorities for a research agenda, focusing on broad approaches that can guide the field.

Guiding principles for a modern GIScience research agenda

A consistent theme during the meeting is that the field of GIScience, and more broadly geography, urban and regional planning and allied fields, must move the goal of *creating a better world* forward on the disciplinary research agenda. While the need for actionable research designed to create local-to-global solutions is not new, the multifaceted and multi-scalar nature of disruptive challenges has sharpened the need for research attuned to cascading effects across locations, time, and social strata. Using place as a system for indexing the world, GIScience naturally lends itself to the development of solutions that consider complexity, contextual effects, human-environment interactions, and flows. However, the balance between using GIScience to: (1) discover new domain knowledge that can be used to change the world, and (2) build the foundational infrastructure for spatial data analytics has shifted in favor of the latter. Merging these two streams and orienting the resulting effort toward disruptions, such as climate change and societal transformation, will contribute to building a better world. We believe this goal and approach can act as a metaphorical lighthouse for the GIScience community. Addressing both research streams will enable researchers, practitioners, decision makers, and funding agencies to navigate the choppy seas of disruption. To facilitate this shift, we define three guiding principles: (1) focusing on the relevance and real-world impact of research, (2) adopting systems-based thinking and contextual approaches, and (3) emphasizing inclusive practices (Figure 1).

Focusing on relevance and impact

Early in the field's history, GIScientists were aware of the field's massive potential to inform decision-making (Pickles 1991). Those early insights remain salient and can motivate a continued commitment to connect research to problems and issues of the day. Committing to impactful research is also strategic. Broadly impacting and benefiting society is a central goal of the U.S. National Science Foundation, National Institutes of Health, and other national funding agencies worldwide. Emphasizing

Figure 1. Overview of the modern GIScience guiding principles and elements and priorities of a modern GIScience research agenda.

impact will also aid in attracting bright and diverse minds to GIScience. A notable shift in the motivation of graduate students and junior academics can be observed. They aim to discover knowledge while implementing solutions for a better world. Of course, GIScience will always need fundamental research as the world changes. Subsequently, new methods must be developed and tested in light of those changes. However, even fundamental research can be designed to look outward and consider future applications, generalizability, and impact. GIScience has knowledge and solutions relevant to some of the world's biggest issues, which could be deployed to move beyond traditional research and guide the translation of science into policy and practice. For example, in cases where effective interventions have already been identified, the research needed may be about how to best implement them across heterogeneous locations, or how to work with communities to measure their impacts as things change (Bardin and Kedron 2022).

Adopting systems and contextual approaches

Relevance and impact can be achieved by embracing and leveraging the unique advantages of a geographic approach rooted in systems thinking and consideration of context. Whether linked to social systems (Henderson *et al*. 2002, Binz and Truffer 2017), natural systems (Wu and David 2002, Haines-Young *et al.* 2003), or socio-ecological systems (Binder *et al*. 2013, Sundstrom *et al*. 2023), systems thinking emphasizes the functional connections between its parts that are localized in, and interacting across, specific geographic contexts. Understanding how dynamic behavior emerges from interactions between system components is critical to generating evidence that can be used to create effective interventions that address disruptive change. GIScience can support systems thinking by providing the digital infrastructure needed to represent and analyze a wide variety of interconnected components and evaluate interventions made within them. As adaptations to climate change emerge across the globe, assessments of whether those interventions work, or will work in other locations, will also depend on the infrastructure and analytical techniques of GIScience. Stated simply, location is the common support for the diversity of data needed to analyze complex, disruptive change; and GIScience is the discipline that develops foundational knowledge on how to represent, analyze, and communicate location data. For this reason, GIScience and the systems and contextual approaches it supports can be the cornerstone of efforts to create a better world.

Emphasizing inclusive practices

The challenges facing the world require an 'all hands on deck' approach, and while the idea of everyone working together is conceptually attractive, the practice of inclusion is surprisingly hard because it requires individuals to restructure their approach and even fundamentally change what is valued (Nelson *et al.* 2022). Inclusion is foundational to GIScience, reflecting the field's long-standing commitment to participatory methods, specifically Participatory GIS. As such, inclusion is not just a contemporary ideal but a continuation of GIScience tradition, involving various voices, actors, disciplines, and viewpoints in the research process (Brown and Kyttä 2014). The principle of inclusion is increasingly crucial as we face global challenges, requiring us to harness the collective strength and wisdom of all. Hence, the concept of inclusion needs to evolve to empower participation of other academic disciplines, people, and communities from a broad range of racial, ethnic, and indigenous backgrounds, genders, abilities, sexual orientations, and other identities. Inclusion also means actively engaging with and respecting the voices, lived experiences, and knowledge of different groups, especially those that are underserved or historically oppressed. The practice of inclusion is an ongoing process that requires continuous dialogue and feedback.

Elements of a modern GIScience research agenda

Guided by the goal of making a better world through GIScience and the principles of focusing on relevance and impact, adopting systems thinking and contextual approaches, and emphasizing inclusive practices, we highlight several research priorities for GIScience in terms of *what* we should focus on (Data and Infrastructure, Artificial Intelligence, and Causality and Generalizability) as well a *how* (through Impactful Open Science, Collaborative and Convergent Science, and through Diverse Participation and Partnerships) we face disruptions.

Data and Infrastructure

GIScience is increasingly data-led; new areas of inquiry open as new sources of data become available (Miller and Goodchild 2015). Engaging with developments that are advancing data is a strength, not a weakness, particularly when these engagements advance methods, theory, and/or provide actionable insights into the dynamic social/physical world. Given this data-led nature, ensuring healthy disciplinary growth requires a number of actions from the scientific community, as described below.

First, it is essential for GIScientists to engage in the data production process (Arribas-Bel *et al.* 2021) so that the resulting data can ultimately be used for spatial data analysis and the limitations and assumptions are transparent. Collaborative data production requires direct engagement with data producers to ensure that spatial data enables scientific inquiries around geographic concerns. This engagement can also mean designing data models that are capable of capturing complex social/environmental processes at high spatial and temporal frequency. Additionally, collaborative data production necessitates the ability to quantify phenomena that are typically overlooked in datasets and digital traces, such as those pertinent to underrepresented populations or remote/sparsely populated areas. Engaging with the data production process is also key to overcome ethical considerations around data access.

The rise of novel sources of digital spatial data has opened unique opportunities to measure social and environmental processes in real-time, at higher spatial and temporal resolution, and by an increasingly diverse ecosystem of providers (Rowe *et al*. 2023). However, the evolving nature of data and the complexity of the data provider ecosystem mean that data are often patchy with uncertain provenance. For example, many forms of widely used 'data' are often produced from models that attempt to estimate missing values, such as Google's demographic ad-targeting database, which often estimates a person's gender based on the websites they visit. In the United States, the official source of income data (the American Community Survey) estimates income *via* a statistical model for nearly 1/3 of respondents, meaning that 1/3 of the income 'data' in the United States is actually modeled (US Census Bureau 2015). This practice of 'measure what you can, model the rest' changes the nature of uncertainty in data whereby uncertainty no longer has a well-understood theoretical distribution and varies in ways that are difficult to characterize formally. Moreover, recent advances in AI mean that 'data' can often be the output of proprietary models with billions of parameters. For example, foundation models such as the NASA-IBM Prithvi model, which can be used to fill in missing or occluded pixels in satellite imagery data, are trained on a broad set of unlabeled data, making it difficult to characterize an error distribution. These developments place a number of new demands on the discipline, and addressing these challenges is where the GIScience community has and should continue to make contributions.

Another key challenge is spatial data integration, which is critical in developing a comprehensive understanding of the factors underpinning and representing social or environmental processes. For example, smartphone apps only generate observations in specific locations at a point in time to capture mobility but often do not gather information on the individuals themselves or places. In addition, varying rates of app usage across the population generate biases and unrepresentative data (Rowe *et al*. 2023). Additional data layers are thus needed to render relevant contextual information, correct existing biases in the data, and validate the reliability of the outputs. Often, scientific discovery requires the integration of many data sets to both ensure geographic coverage (different areas may have different data sources) and coverage of the domains of interest (e.g. integrating human activity data with satellite data). This integration process can introduce and conflate error and uncertainty from multiple sources. Furthermore, complex models used in these integrations inherently come with model uncertainty, which arises from various factors such as data quality, model assumptions, algorithmic bias, parameter estimation, and the interaction effects between integrated datasets. Moreover, the increasing size and complexity of data means that "download and analyze" is increasingly not a viable pattern of inquiry in the spatial sciences, despite the temptation of quick results. Increasingly, computation and analysis need to be moved to the data streams, as opposed to the other way around. GIScience as a field has the tools and expertise to build a modular approach for integrating spatial data across domains in a way that can handle uncertainty and apply geographic principles like scale and resolution (see e.g. (Şalap-Ayça and Jankowski 2016, Oshan *et al*. 2022, Markham *et al*. 2023). By using these tools and expertise, GIScientist can improve the robustness and credibility of their findings, ensuring that the outputs are not only accurate but also reliable and informative for decision-making.

The growing complexity and heterogeneity of the data landscape means that the cost to an individual researcher for acquiring, storing, and processing the best available data for a given problem can be very high. For example, mobility insights data that were made available at no cost at the start of the COVID-19 pandemic by big tech companies (Noi *et al.* 2022, Wang *et al*. 2022) now require academic licenses that cost researchers thousands of dollars per month. Moreover, despite the fact that the fundamental importance of high-performance computing (HPC) as a paradigm for spatial analysis has been recognized by the community for decades (Turton and Openshaw 1998), many researchers still experience barriers to access. Even organizations with HPC capabilities can have access limitations due to funding constraints, competing research agendas, or technical expertise gaps. Data access and computing often bears other costs, such as requiring connections at data producers (Olivera *et al.* 2019), expertise for big data computing, and capability to manage updates to data as new data production methods often yield data streams rather than data sets. These costs require concentrated efforts to maintain strategic interdisciplinary partnerships and build technical expertise either internally or by outsourcing qualified specialists to assist with code and methods design and validation. Historically, GIScience concentrated community efforts to enhance digital infrastructure, which laid the groundwork for the multiple research efforts that were critical for progress (Goodchild and Haining 2004). Today, infrastructure is important to enable not only original research but also reproducible research that aids systems thinking approaches and can capitalize on big spatial-temporal data.

Artificial intelligence

Artificial Intelligence (AI), particularly generative AI and large language models (LLMs) like ChatGPT, are poised to drastically alter society akin to how the steam engine, electricity, and the internet shifted global economic, environmental, and social structures in the past. Given GIScience's strong foundation in technology, it is increasingly imperative for the field to not only adapt to these burgeoning technologies but also take a leadership role in shaping them so they are appropriate for geographic approaches. While AI has been used in geography for decades (Smith 1984, Openshaw and Openshaw 1997), the field of GeoAI (Janowicz *et al*. 2020) is advancing with force and leveraging AI technologies to develop spatially explicit and spatially implicit prediction AI models that build on the expertise of GIScientists and domain experts. A variety of efforts demonstrate the tremendous opportunities for integrating AI into GIScience, including work in geometric AI for image analysis (Miolane *et al*. 2020) and applications of the First Law of Geography for GeoAI developments (Li *et al.* 2021). However, little is understood about how the First and Second Laws of Geography will be impacted by, or understood, in the age of AI. Moreover, recent discoveries have shown that LLMs like ChatGPT have an impressive ability to learn rich spatial and temporal representations of the real world (Gurnee and Tegmark 2023). This revelation can further inspire GIScientists to utilize such representations in exploring geographical phenomena more effectively. Notably, OpenAI's LLM 'Sora' was developed under a world model (Brooks *et al*. 2024), enabling it to better learn geographical patterns and rules. These findings suggest capability for better integration with space, time, and geographies, implying exciting prospects for future innovative developments in GIScience.

However, the integration of AI in GIScience carries multifaceted challenges. First, the "black box" nature of AI algorithms presents challenges in understanding their complex workings, which are crucial for informed decision-making. Spatial data exhibit unique characteristics that allow for identification and prediction through exploiting spatial patterns. While identifying patterns is not unique to GIScience, leveraging features of geographic data like spatial autocorrelation opens up a new level of complexity that may be abstracted from AI 'users.' Second, AI in GIScience can also experience overfitting, where models perform well on training data but poorly on new data, leading to inaccuracies in predictive models that impact real-world decisions. Third, data and algorithmic biases can impact models and results. For instance, AI models for urban development, when the models rely solely on land use change observed from satellite imagery, might not accurately represent developing or rural areas if trained predominantly on data from developed cities. There are also specific challenges for society and geographies. Deepfake technology exemplifies AI's dual impact. While beneficial for recreating historical landscapes, *deepfake* satellite or aerial images pose risks to national security and privacy (Zhao *et al*. 2021). Additionally, predictive policing models using AI to forecast crime, if not carefully managed, can result in overpolicing in certain communities, often disproportionately affecting marginalized groups (Alikhademi *et al*. 2022).

The growing integration of AI into GIScience highlights the need for a comprehensive, humanistic approach to effectively address the resultant challenges (Zhao and Feng 2024), including revisiting and possibly updating the existing GIS code of ethics, enhancing GIS literacy, and promoting responsible AI practices within the field. Developing an ethical framework for AI in GIScience involves creating guidelines to ensure fairness, transparency, and accountability in AI applications. It also involves interrogating and establishing data privacy 'best practices' as location data are particularly susceptible to privacy violations and exposures. Promoting AI literacy is also critical and requires GIScientists to gain a deep understanding of AI technologies and strengthen collaborative links with computer and data scientists. In practice, responsible, explainable, and equitable AI practices must be adopted in GIScience to address challenges inherent in AI integration.

Causality and generalizability

Most human and environmental phenomena are non-randomly distributed across space, making it easy to find correlations among spatial data that may be unrelated to the underlying mechanisms responsible for those spatial distributions. This reality complicates the identification and establishment of causal relationships, and it requires developing and integrating specialized techniques that can isolate and eliminate the obscuring effect of spurious spatially-induced correlations (Gibbons and Overman 2012, Herrera Gómez *et al.* 2014, Kolak and Anselin 2019, Reich *et al*. 2021, Gao *et al*. 2022). These techniques are not, however, solely statistical or computational. Two central challenges in causal research remain: first, identifying and specifying a reliable approximation of the data-generating process, and second, setting up an appropriate counterfactual for inference (Harvey 1969, Yeung 2023, Zhang and Wolf 2024). These intertwined conceptual challenges require researchers to develop a closer relationship with theory, past empirical evidence, and contextual knowledge. Specifying the data-generating process and setting up counterfactuals are essential to identifying alternative explanations that need to be controlled to make valid causal inferences (Rowe 2023). Counterfactual frameworks underpin common causal inference methods such as matching, instrumental variables, and regression discontinuity designs (Morgan and Winship 2007). They are fundamental to drawing valid inferences about the causal impact of actions, interventions, or policies. However, a widely adopted and systematic approach to the challenge of identification and counterfactual construction in spatial causal inference has yet to emerge and should be an area of focus if geographers and GIScientists intend to join the wider movement toward causation that is observable across the social and environmental sciences (Zhang and Wolf 2024).

At the same time, ongoing advances in spatial analysis, rising computational power, and the availability of detailed spatial data have created the opportunity to pursue more accurate and robust causal inference in spatial contexts (Gao *et al*. 2022, Li 2022, Xin *et al*. 2022, Hoffman and Kedron 2023). An explosion of AI and ML research is pursuing an intriguing but distant data-driven approach to causal inference. AI and ML approaches that focus on boosting predictive performance may generalize statistically (e.g. train/test/validation error) but not contextually (e.g. across locations). Such techniques presently lack a clear strategy to identify different causal mechanisms at different places and times. GIScientists are generally well-positioned to weigh in about contextual generalizability, but more work is needed to build contextual awareness into the counterfactual frameworks needed to identify causal relationships (Zhang and Wolf 2024). It remains unclear how to consistently and reliably propose what would have happened in a location without a particular intervention when the effect of interventions in surrounding areas may spill over across regions. Specifying a model that accurately captures the complex spatial dependencies between causal mechanisms is still more challenging. Traditional statistical models are likely insufficient in these cases, necessitating advanced spatial econometric models to handle spatial dependencies (Reich *et al*. 2021, Akbari *et al.* 2023). There are promising opportunities for GIScience to work on these issues with other fields, including economics and engineering, mathematical work in Bayesian networks of conditional probabilities, social science extensions to structural equation models, and big data in bioinformatics (Manson 2023).

When building the foundations for spatial causal analysis, GIScientists will benefit from maintaining a watchful eye on several research areas. First, it is essential to consider how context is represented in causal models, particularly those driven by ML and AI. In these approaches context is often learned by the model and opaque to the analyst. While this may not threaten the predictive capacity of the resulting model, it can undermine causal inferences because it is similarly unclear how the central causal effect is identified and what alternative explanations are accounted for in the model. Second, adequate reporting and description of geographic contexts used in a causal model is paramount for supporting reproducibility, which is important for checking the veracity of results and facilitating replications, which are essential to demonstrating the generalizability of results. Building and adopting open science practices, such as pre-registration, to avoid accidentally discovering non-causal patterns, will be critical. Relatedly, evidence of the replicability of causal effect across locations is fundamental to any movement toward reliable intervention in the real world and collaboration with policy-makers, government officials, and community leaders. A primary concern of these groups is creating effective, scalable change in the world in response to disruptions. The capacity to provide and communicate reliable evidence of the causal impact of interventions will be essential to engaging and supporting these efforts, as will welcoming their involvement in the design, implementation, and evaluation of future interventions. Finally, GIScientists must develop and deploy training and tutorials for spatially explicit causal methods and advocate for their use. These steps will be invaluable in moving beyond prediction and, more broadly, analyzing and influencing interventions.

Impactful open science

Open science is defined by the sharing of research data, methods, and findings, and it can play a significant role in the advancement of GIScience (Rey 2009). The increased accessibility to research artifacts enhances the reproducibility of research and accelerates the pace of innovation in science (Munafò *et al*. 2017). This facilitation is especially crucial in GIScience due to the challenges posed by the large volume, complexity, and diversity of spatial data, which are inherent obstacles to scientific reproducibility (Kedron *et al*. 2021). Key factors contributing to the reproducibility crisis in science are the mixing of exploratory and confirmatory analyses (Wagenmakers *et al*. 2011), the 'big data avalanche' alongside, and the rise of ML/AI. Collectively, these factors have exacerbated the blurring of exploratory and confirmatory analysis in GIScience. Open science practices, such as study preregistration, stress this distinction and separate exploratory analyses from confirmatory hypothesis testing (Allen and Mehler 2019).

While adopting open science practices in GIScience offers much potential, there are barriers. The costs of ensuring reproducibility are substantial and disproportionately borne by scientists (Rey 2023, Kedron *et al.* 2023). Platforms are needed that can facilitate reproducibility while spreading the cost burden across the community (Boeing

2020, Kedron *et al*. 2021). Additionally, the growth in research artifacts and open science products, such as data, code, computational notebooks and preprints, feedback new challenges and disruptions to the scientific ecosystem (Arribas-Bel *et al*. 2021, Rowe *et al*. 2020). Therefore, new consensus mechanisms are warranted to help researchers, and the public more broadly, deliberate over evidence and advocate for particular hypotheses or artifacts. GIScience should focus, in particular, on frameworks for capturing consensus across space, which is closely related to crowdsourcing and volunteered geographic information (VGI). The transparency of the full data lifecycle and associated analytical decisions employed in research are increasingly important as are the development of heterogeneous data sources and complex methods. New tools in the blockchain and distributed ledger space offer potential solutions for tracking provenance and the veracity of spatial data but require further evaluation. In the classroom, the adaptation of tools that highlight the impact of researcher decisions (Kedron *et al*. 2022) and the adoption of pedagogical models that use replications as a form of project-based learning (Kedron *et al*. 2024) can prepare the next generation of geographic researchers to address these challenges.

Another foundational concept that is crucial for reproducibility is explainability. It ensures that methods, data, and reasoning are clear and understandable and allows others to replicate the study accurately and understand how and why certain conclusions were reached. Explainable science is essential for public trust, informed governance and the productive application of GIScience in societal and environmental contexts. This means that beyond being able to reproduce someone's research, there must be clarity on how, why, and in what contexts the research can be applied (Gahegan 2023). This deeper understanding is critical for the practical implications of GIScience in modeling and governing social and environmental systems.

Lastly, the push for openness in GIScience must be balanced with concerns related to privacy and research credibility, and there are opportunities for GIScientists to contribute to solving these issues. The sharing of spatial data, especially those that can be linked to individuals' locations and behaviors, raises significant privacy issues (Richardson *et al*. 2015). Therefore, open GIScience initiatives must implement robust data anonymization and privacy protection measures to safeguard individuals' privacy. Additionally, ensuring the credibility of open spatial data and research findings requires rigorous peer review processes and standards for data quality and reproducibility. By addressing these challenges, an open GIScience approach can maximize its potential benefits while minimizing risks, leading to more informed, equitable, and effective solutions to spatial challenges.

Collaborative and convergent science

Collaborative and convergent science has the goal of co-creating knowledge in a manner that can inform management and decisions by involving scientists, policy makers, communities, and others to advance understanding in a manner that each group could not achieve working alone.

There is widespread agreement that academic structures, which remain largely organized around traditional disciplines in which research is siloed, are a barrier to collaborative science and hinder responses to contemporary 'grand challenges' and 'wicked problems' (Kawa *et al*. 2021). This approach, embedded in decades of academic research practice, has generally been limiting, as problems are tackled using a narrow set of objectives, perspectives, and methods and findings are published to a confined audience in discipline-specific journals. The shortcomings of this approach have become more apparent as the risks associated with complex, massive challenges such as climate change have become more pressing, and there is growing evidence that impactful research requires input from many disciplinary perspectives and voices coming together to investigate, develop, and test potential solutions. Evidence of this need can be seen in funding calls from the U.S. National Science Foundation, the UK Research and Innovation, the European Research Council and other agencies stressing convergent approaches and collaborative, team science.

Collaborative and convergent science requires a "common key" that links discipline-specific questions, approaches, and findings together into a comprehensive and comprehensible whole. GIScience and geography (and GIScient*ists* and geograph*ers*) are naturally positioned to lead and contribute to these collaborative efforts. First, the nature of the discipline of geography is itself interdisciplinary, fusing physical and human, quantitative and qualitative. For GIScience, this interdisciplinarity has stimulated the development of a social-science inflected analytical sub-field that ably straddles information/computer science and social science and provides a broad foundation for input and collaboration. Second, as is frequently noted, everything happens *somewhere*—location and place often provide that common key that joins disparate perspectives and methodological approaches. Third, a unique aspect of the wicked environmental, social, and economic problems facing us is that they are multi-scalar in both cause and effect, with impacts that compound and interact across spatial scales. Neighborhoods impacted by increased flood risk, for example, are affected by local planning decisions, but also regional environmental policy, and global climate shifts. GIScientists are uniquely placed to engage and lead on these multi-scalar issues, both conceptually and methodologically.

That said, there remains a sizable gap between actual and potential collaborative and convergent science, as well as the prospective role of GIScience in evolving scientific paradigms. Formidable barriers, which include traditional models of graduate education and long-established, slow-to-evolve academic promotion criteria, will require systemic change. Other challenges are easier to address such as increasing the visibility of GIScience by extending our voice outside the discipline and heightening awareness of what spatial scientists bring to the table in terms of expertise and experience. GIScientists can also challenge themselves to ask bigger questions and make more impactful contributions, for example by changing how they engage community partners and teach students. One particular area of tension is the often natural overlaps between the thematic foci of computer and data scientists and GIScientists (Huang 2022), yet these synergies sometimes trigger disciplinary border policing rather than collaboration, leading to dead-end conversations. Here, GIScience would do well to emphasize its unique capacity to engage with the social and natural sciences. Indeed there is an art in knowing when to lead and when to follow, and GIScience, like all other disciplines, can thrive through adopting multiple types of roles to create a research culture that recognizes the value in converging many different fields.

Diverse participation and partnerships

Inherent in a response that will create collaborative and convergent science is broadening the diversity of our GIScience teams. Inclusion, along with equity, must be considered in every aspect of GIScience work and be centered in GIScience if we are to meet all other goals (Nelson *et al.* 2022). Creating a more diverse GIScience field is not a new goal. Twenty years ago, a 2004 President's Column from the newsletter of the American Association of Geographers (AAG) (Lawson 2004) focused on diversifying geography and the benefits that would come from its diversification. Yet, evidence from the adjacent field of geoscience suggests that we are not making the desired progress; as of 2018 only 3.8% of tenured geoscience faculty in 100 top departments were people of color (Bernard and Cooperdock 2018). Gender and geographical representation on journal editorial teams has also been slow to progress in GIScience and quantitative geography (Franklin *et al*. 2021). Scientific fields, backed by structural and social factors, encourage participation that reinforces dominant culture. For example, women, Black and Hispanic people, and people with diverse gender and sexual orientations have lower rates of participation in many science fields (Dutta *et al.* 2021). Champions are emerging though. For example, NorthStar of GIS is a group that aims to increase representation of Black people in GIS and has the mission of advancing intersectional racial justice and belonging in GIS, geography, and STEM. Support, including financial, of Black-led GIS initiatives is one powerful way to amplify the impact of these organizations and create opportunities for diversification of people in GIScience. Efforts to democratize access to GIScience through easy to use or open software and broadly-applicable curriculum can also increase participation by lowering barriers to entry and use. I-GUIDE, the NSF-funded Institute for Geospatial Understanding through an Integrative Discovery Environment has made massive strides in creating access to HPC infrastructure and is an example of how science can lead to more accessible technology (Michels *et al.* 2024). Diversifying the kinds of questions that are asked in GIScience is another way to build a more inclusive field that understands how space and place matter for all (Franklin *et al*. 2023).

In addition to diversifying who does GIScience, there is a need to expand how GIScientists partner with policy makers and the wider community. The COVID-19 pandemic highlighted the spatiality of public health risks and policy solutions. GIScience research and tools mapped trends and anticipated emerging risk (Kolak *et al*. 2021) and tracked stay-at-home orders across the globe using GPS data from mobile phones (Gao *et al*. 2020, Kang *et al*. 2020, Wellenius *et al*. 2021, Alessandretti 2022), while reiterating the value of integrating GIScience expertise with policy. While the pandemic presented an especially pressing and ubiquitous policy challenge, the need to integrate GIScience with public policy has never been clearer and can guide us in building partnerships with policy makers in three ways. First, while GIS software knowledge is widespread throughout industry, government, and non-governmental organizations, the *principles* of spatial relationships and their ethical interpretation need to be emphasized beyond their standard constraints within software programs. Second, impact partnerships can be facilitated through disciplinary translation and building domains of knowledge in substantive areas of policy. In housing, for instance, core concepts such as 'opportunity' have definitions combining racial segregation, poverty, educational outcomes, health, and labor market outcomes, which varies by governing bodies and regions. The GIScience field can foster credibility through our ability to share common terminology and concepts, which will enable greater enthusiasm for the existing interest in novel methods and data sources. Third, GIScience efforts to partner with policy makers will have network effects. Successful partnerships not only build trust and deeper engagement with areas of domain expertise but also enable other opportunities for engagement through sharing success stories, building networks, and growing GIScience knowledge amongst policymakers.

Community partnership is also critical to the work of the GIScientist in an age of disruption. A more diverse field will still lack the range of lived experiences and perspectives necessary to support the kinds of questions we want to answer. Beyond partnerships with decision makers the field also needs partnerships with community organizations in order to be able to connect with people living in the places under study. For example, studying the impacts of extreme heat events will only be done effectively if communities who have experienced and are disproportionately impacted by those events are involved in every aspect of the research. Like co-designing with interdisciplinary collaborators, co-designing research questions with community partners is required to ensure our research generates solutions that will work. Open science, which has emphasized democratization of participation, offers examples that can guide our efforts in creating partnership with communities (UNESCO 2023).

Discussion

Disruptions are changing the practice of science across many fields and shifting the way in which scientific problems are approached. While some of these disruptions stem from shifts in environment and society, such as the COVID-19 pandemic, climate change, and the biodiversity crisis, others have emerged from technological developments, such as the explosive growth of generative artificial intelligence and the rapid advancement of high-performance computing. Given GIScience's identity as an information science while also being situated within geography, with domain expertise on physical, social, and human-environment relationships, the field is uniquely positioned to both lead and contribute to advances that leverage all types of these disruptions. A few key themes emerged from ongoing discussions that started during a meeting in Santa Barbara in December 2023. These themes are synthesized below with actions highlighted.

We first organized the discussion around three guiding principles that should orient our work in GIScience as we address and adjust to disruptions: (1) focusing on the relevance and real-world impact of research, (2) adopting systems-based thinking and contextual approaches, and (3) emphasizing inclusive practices. While we have always integrated these facets to some degree in our research, it is becoming increasingly more important to ensure the field is continuing to build a healthy science that goes beyond simply applying methods to spatial data and focuses on discovering new forms of knowledge that can help us address the myriad challenges facing the world. We then detailed six research priorities for what GIScience should focus on moving forward, and how we should do that, to build a modern GIScience research agenda.

Those priorities include: (1) Data and Infrastructure, (2) Artificial Intelligence, and (3) Causality and Generalizability, (4) Impactful Open Science, (5) Collaboration and Convergence, and (6) Diverse Participation and Partnerships. Below we discuss how shifting the ways in which we approach science can foster the gains in GIScience.

Balancing 'slow science' with the need for rapid, real world response

There have been calls for science to *slow down* (Stengers 2016). Slow science recognizes that professional demands including academic tenure and promotion, publisher profits (Koerber *et al.* 2023), and other factors have created pressure to publish minor or incomplete findings. This 'fast' approach to science not only increases the burden on reviewers and editors to handle an increasing volume of submissions, but it renders it increasingly difficult to identify high-quality and important research. In contrast, slow science centers on research quality, where researchers have time and space to discuss, examine, and reflect upon science, technology and 'progress' and to situate themselves in their communities and neighborhoods (Stengers 2016) in order to respond to issues and co-create solutions. GIScience is especially prone to acceleration because data can now be found almost anywhere and can be analyzed quickly. However, most disruptive, groundbreaking science requires time. It is slower in nature. Effective inclusion also requires slowing down to ensure that participation is meaningful and can accommodate different ways of knowing and understanding the world. It is important to stop and ask "for what purpose and what impact?"

There is a need to balance slow science with the need for practical and policy-oriented research that has real world impact. Indeed, the wicked problems that are disrupting our world sometimes need a rapid response. Following the first guiding principle to focus on the relevance and real-world impact of our work, GIScientists can help strike this balance. These practical and policy-oriented projects often do not produce the same type of outputs that are incentivized by fast science in academia (i.e., publications in peer-reviewed journals). Instead, outputs can be decision support web tools, white papers, or even the formation of a community of practice. Recalibrating our incentive structures and creating different types of outlets (e.g., replications, shorter format notes, etc.) for different types of research could actually have the effect of helping to slow down science while simultaneously fostering a shift to real-world impacts.

Centering 'spatial' to advance the field together

Spatial data and methods are now broadly used across many fields, which is a positive outcome for the field given the range of impacts and decisions that are being supported with GIScience. Some of the most interesting spatial developments, such as GeoAI, are leveraging multidisciplinary teams of engineers and computer scientists to advance methods. As more teams leverage geographic data science, our toolbox will most certainly grow, creating more opportunities for impact. However, one challenge that arises from this success is that the field of GIScience has become distributed, and it can be hard to determine what constitutes impactful 'GIScience research'. So, while we look outward to where we can have the most benefit and impact, it is also necessary to look inward to the core to reflect on how we can continue to advance GIScience as a science while also using GIScience to support other fields of inquiry.

Centering 'spatial' and a geographic approach requires us to rethink the curriculum taught to GIScience students. Most GIScience programs in the United States, and indeed around the globe, use a core curriculum developed in the 1990s. However, it is an opportune time to rethink the core principles that should be taught across levels of instruction. In the rapidly changing technology environments there are also important theories that will prepare students to address the array of research priorities discussed here. In short, a modern GIScience curriculum is needed as a lighthouse to guide instructors, researchers, and practitioners as they work to solve the world's problems and educate the next generation of GIS developers, users, and makers.

Bold directions

Change is normal, but the level of disruption we are currently experiencing is a result of new climate, social, and technological processes. As such, our response needs to also be different, and, we argue, bolder. We present three areas where bold changes are needed.

First, all GIScience students should receive training in *spatial* analytics. Many students receive general training in data science and analytics but GIScience students are specifically trained to recognize and handle the nuances of spatial data. Ensuring that GIScience graduates have received explicit training in spatial analysis will help prepare them to select analytical tools and methods that are appropriate to respond to the questions being asked and the data being used. Providing robust training in spatial analytics will ultimately differentiate GIScence students from simply data scientists working with spatial data.

Second, geographical systems thinking should be integrated into analyses and evaluated during peer-review. Few papers being published in the GIScience literature are addressing complex challenges head on, which means there is an untapped opportunity to create stronger impacts. If every GIScientist committed to increasing the percentage of their research that addresses complex climate and social challenges, it would fuel new interdisciplinary and community partnerships, advance research in new directions, and help train a generation of GIScientists prepared to take on the grand challenges that are certainly headed our way. Research that leverages a geographical approach to systems thinking can also help shift what is valued when papers, funding, and tenure and promotion are reviewed. We can purposefully work to disrupt the field as a positive response to the disruptions happening around us.

Third, and stemming from the prior point, tenure and promotion criteria in the field need to evolve to recognize and reward impact in new ways. It is common for disciplines to value many forms of excellence, and external reviewers have a voice in what type or forms of work are elevated as contributions. As reviewers, we can all make an effort to point out impactful work during peer-review, particularly if that work does not fit the traditional model. We choose what to uplift, and we should be more proactive in determining how to value non-traditional contributions that improve equity, reduce impacts of social and climate change, and generally make the world better.

Conclusion

Disruptions in science and society appear to be accelerating, and for the foreseeable future, these disruptions are likely to be the norm. How we respond to disruptions sets the stage for the future of GIScience research, and by extension geography. We set forth three principles that can guide GIScience research during this time, including focusing on the relevance and impact of our work, adopting systems and contextual approaches that leverage our interdisciplinary expertise, and emphasizing inclusive practices. While it is an exciting time to be working at the interface of geography and information science due to the massive potential for positive impact, it is critical that we pause and respond with intention. Embracing change is necessary, but we must also be mindful that the discipline has a critical role to play in shaping the future of science and society. We hope this paper starts a conversation about how GIScience can lead in a time of disruptions and that these conversations continue into the future.

Acknowledgements

The authors acknowledge generous support from Esri (Environmental Systems Research, Inc.) as well as Jack and Laura Dangermond. Support was also provided by the Center for Spatial Studies and Data Science at the University of California, Santa Barbara. The authors would like to acknowledge Sarah Bardin from Arizona State University for her help capturing the lively discussion and Shaine Lutsky for her help organizing the meeting and assisting with figure creation and overall administration. S. Dodge acknowledges support from the National Science Foundation (award BCS #2043202).

Contributions

All authors participated in a workshop to generate ideas and topics that led to this paper. Authors contributed writing and editing. Nelson, Frazier, and Kedron led the editing and structuring of the paper

Disclosure statement

No potential conflict of interest was reported by the author(s).

Notes on contributors

Trisalyn Nelson joined the Department of Geography at UCSB as Jack and Laura Dangermond Endowed Chair of Geography in 2020. Previously, she was Director of the School of Geographical Sciences and Urban Planning at Arizona State University and the Lansdowne Research Professor and Director of the Spatial Pattern Analysis and Research Lab at the University of Victoria, Canada. Dr. Nelson values partnerships, particularly connections between industry and academics, that enable innovation of methods and approaches to solving critical issues.

Amy E. Frazier is a professor and the Jack and Laura Dangermond Endowed Chair of Conservation Science at the University of California, Santa Barbara. Her research sits at the nexus of GIScience, remote sensing, and landscape ecology and harnesses large biological and environmental data to assess conservation outcomes and inform decision making. She teaches courses in GIScience and Remote Sensing.

Peter Kedron is an Associate Professor of Geography at the University of California Santa Barbara and Associate Director of the Center for Spatial Studies and Data Science. He develops analytical methods, research approaches, and pedagogical models to build a reproducible and reliable spatial data science. His recent research focuses on bringing a geographic approach to understanding not only what policies work, but what policies work where.

Somayeh Dodge is an associate professor of spatial data science at UC Santa Barbara, where she leads the MOVE Lab and serves as an associate director at the Center for Spatial Studies and Data Science. She holds a Ph.D. in Geography from the University of Zurich. Her research focuses on developing spatio-temporal data analytics, machine learning, modeling, and visualization techniques to study and understand movement in human and ecological systems.

Bo Zhao is an associate professor in the University of Washington's Department of Geography and director of the Humanistic GIS Lab. His research focuses on GIScience, spatial misinformation, and the societal implications of emerging GIS technologies and is particularly invested in understanding and addressing the experiences of vulnerable populations, such as refugees displaced by climate change effects and LGBTQ+ communities in repressive national contexts. Dr. Zhao's contributions to the academic community have been recognized through numerous accolades, including awards from prestigious organizations such as the National Science Foundation, National Geographic, and Samsung.

Michael Goodchild held the Jack and Laura Dangermond Chair of Geography and was Director of UCSB's Center for Spatial Studies until 2012. He received his BA in Physics from Cambridge University in 1965 and his PhD in Geography from McMaster University in 1969, with his research and teaching interests focused on issues in geographic information science, including uncertainty in geographic information, discrete global grids, and volunteered geographic information. Dr. Goodchild moved to Seattle upon retirement and currently holds a part-time position as Distinguished Chair Professor at Hong Kong Polytechnic University.

Alan Murray is a Professor in the Department of Geography and leads the Wildfire Resilience Initiative at UCSB. His research and teaching interests focus on geographic information science, spatial optimization, emergency response, health informatics, urban growth and development, land use planning, urban, regional, and natural resource planning and development, and, infrastructure and transportation systems.

Sarah Battersby is a Senior Product Manager at Esri for the ArcGIS GeoAnalytics products. Sarah holds a PhD in Geography from the University of California at Santa Barbara.

Lauren Bennett is Product Engineering Director of Spatial Analysis and Data Science at Esri where she oversees research and development for data analysis features within the company's geographic information system (GIS) software systems. Since joining Esri in 2007, Lauren also has served as Software Development Team Lead, Spatial Statistics Product Engineer, and Federal Solution Engineer. She earned a bachelors and master's degree in geography from McGill University and George Mason University, respectively, and a doctorate in Information Science from Claremont Graduate University.

Justine I. Blanford is a professor of GeoHealth at ITC, University of Twente and geospatial scientist working at the intersection of geospatial sciences and health. Her work focuses on better understanding different aspects of health risks and outcomes so that we can respond in a timely manner and develop sustainable solutions by analysing and modeling different phenomena at a variety of spatial and temporal scales. She earned a PhD in Biology from Imperial College, UK, an MPhil from the University of Leicester, UK, a BaH from Queen's University, Canada, and learned her GIS skills at the Centre of Geographic Sciences (COGS), Canada.

Carmen Cabrera-Arnau is a Lecturer in Geographic Data Science (Assistant Professor) at the Geographic Data Science Lab, within the University of Liverpool's Department of Geography and Planning, where she specialises in geographic data science, human mobility, network analysis and mathematical modelling. Carmen's research focuses on modelling and predicting human mobility patterns across spatiotemporal scales and population groups, and on establishing methodologies to facilitate the efficient and reliable use of new forms of digital trace data for the study of population movements. Prior to joining the University of Liverpool, Carmen completed a PhD in Applied Mathematics at the Department of Mathematics, UCL, followed by a position as a Research Fellow in Urban Mobility at the Centre for Advanced Spatial Analysis (CASA), UCL.

Christophe Claramunt is a professor of computer science at the Naval Academy Research Institute in France. His research interests include theoretical and multidisciplinary aspects of geographical information science, with applications in urban, maritime, and environmental domains. He currently serves as an associate editor for the International Journal of Geographical Information Science. Among other affiliations, he is a research fellow at the Machine Learning and Data Science Unit at the Okinawa Institute of Science and Technology and at the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences.

Rachel Franklin is a Professor of Geographical Analysis at Newcastle University and Group Lead for Liveability in the Science of Cities and Regions Programme at The Alan Turing Institute (the UK's national institute for data science and AI). Her primary research focus is in spatial demography and the interplay between spatial analytics and demographic change, in particular quantifying patterns, sources and impacts of spatial inequality. She holds a BA in French and Political Science and MA in West European Studies from Indiana University, and a PhD in Geography from the University of Arizona.

Joseph Holler is a human geographer, a geographic information scientist, and Associate Professor of Geography at Middlebury College. He is interested in open science and the reproducibility of geographic research, and in applying geographic research to global challenges of climate change, hazards, social vulnerability, and social inequality and justice. Joseph earned his bachelors degree in anthropology, computer science, and media studies at Ithaca College and PhD in geography at the University of Buffalo.

Caglar Koylu is an Associate Professor of GIScience at the University of Iowa, where he leads the Geo-Social Lab, focusing on the analysis of large geo-social networks and the processes that shape our economy, society, and environment. His recent NSF-funded research explores kinship networks and migration using population-scale family trees and historical census data. Caglar, currently the President-Elect of the Cartography and Geographic Information Society, earned his Ph.D. from the University of South Carolina.

Angela Lee is the Director of Education Solutions at Esri.

Steven Manson is a professor in the Department of Geography, Environment, and Society at the University of Minnesota in the Twin Cities. He also directs the Human-Environment Geographic Information Science lab and is a Fellow of the Institute on the Environment and Scholar of the College in the College of Liberal Arts. Dr. Manson combines environmental research, social science, and geographic information science to understand complex human-environment systems.

Grant McKenzie is an associate professor of spatial data science in the Department of Geography at McGill University. At McGill, Grant leads the Platial Analysis Lab, an interdisciplinary research group that works at the intersection of information science and behavioral geography. Much of Grant's work examines how human activity patterns vary within and between local regions and global communities and this has driven his applied interests geoprivacy and new mobility services as well as the broader role that geographic information science plays at the intersection of information technologies and society.

Harvey Miller is the Bob and Mary Reusche Chair in Geographic Information Science, Professor of Geography and Director of the Center for Urban and Regional Analysis at The Ohio State University. His research focuses on sustainable, resilient and equitable mobility and communities. His honors and awards include the Edward L. Ullman Award for Outstanding Contributions to Transportation Geography and the James R. Anderson Medal of Honor in Applied Geography from the American Association of Geographers, the Outstanding Achievement in Urban Informatics Award from the International Society for Urban Informatics, the Research Award from the University Consortium for Geographic Information Science, and the Community Engaged Scholar Award from The Ohio State University.

Taylor Oshan is an Associate Professor in the Department of Geographical Sciences at the University of Maryland. He is broadly interested in characterizing spatial patterns and processes through the use of quantitative geographic methods, which typically falls under the banners of spatial analysis and spatial statistics, geographic information science, and the emerging discipline of spatial data science. Dr. Oshan received his BA in History from the University of Delaware, his MA in Geography from CUNY Hunter College, and his Ph.D. in Geography from Arizona State University.

Sergio Rey is a Professor of Geography at San Diego State University and his research focuses on spatial data science, geocomputation, spatial inequality dynamics, regional science, and open science. He is a Fellow of the American Association for the Advancement of Science, the Spatial Econometrics Association, and the Regional Science Association International. Rey is Founding Director of the Center for Open Geographical Science, and is the co-founder and lead developer of the open source Python Spatial Analysis Library (PySAL).

Francisco Rowe is Professor in Population Data Science and the Lead of the Geographic Data Science Lab at the Department of Geography and Planning within the University of Liverpool. His research focuses on human mobility & migration, spatial inequality and geographic data science.

Seda Şalap-Ayça is an Assistant Professor of Practice at Department of Earth, Environmental, and Planetary Sciences and Institute at Brown for Environment and Society at Brown University. Her research focuses on spatial decision making and understanding the role of uncertainty in spatial models, particularly for human-environment interactions. She did her Ph.D. in Geography in a joint doctoral program between UC Santa Barbara and San Diego State University where she focused on spatially explicit uncertainty and sensitivity analysis methods for land use models.

Eric Shook is an Associate Professor in the Department of Geography, Environment, and Society at the University of Minnesota in the Twin Cities. His research is focused on geospatial computing, which is situated at the intersection of geographic information science and computational science, with particular emphasis in the areas of cyberGIS, geoAI, and geospatial data science.

Seth Spielman is a Director and Principal Data Scientist at Microsoft AI.

Wenfei Xu is an assistant professor in urban planning in the Department of City and Regional Planning at the College of Architecture, Art, and Planning at Cornell University and Director of the Urban Data Research Lab. Her main research traces the legacies of historical structural disinvestment and asks how they have shaped present-day inequality and processes of neighborhood change.

John Wilson Ph.D., is Professor of Spatial Sciences and Sociology in the Dana and David Dornsife College of Letters, Arts and Sciences at the University of Southern California (USC) where he is founding director of the Spatial Sciences Institute. His research focuses on the modeling of environmental systems and makes extensive use of GIS software tools, fieldwork, spatial analysis techniques and computer models.

ORCID

Amy E. Frazier http://orcid.org/0000-0003-4552-4935
Peter Kedron http://orcid.org/0000-0002-1093-3416
Somayeh Dodge http://orcid.org/0000-0003-0335-3576
Bo Zhao http://orcid.org/0000-0002-7834-6672
Alan Murray http://orcid.org/0000-0003-2674-6110
Sarah Battersby http://orcid.org/0000-0003-2716-4382
Lauren Bennett http://orcid.org/0000-0002-5637-6942
Justine I. Blanford http://orcid.org/0000-0003-0844-9390
Carmen Cabrera-Arnau http://orcid.org/0000-0002-2732-6436
Christophe Claramunt http://orcid.org/0000-0002-5586-1997
Rachel Franklin http://orcid.org/0000-0002-2614-4665
Caglar Koylu http://orcid.org/0000-0001-6619-6366
Steven Manson http://orcid.org/0000-0001-7697-5339
Grant McKenzie http://orcid.org/0000-0003-3247-2777
Harvey Miller http://orcid.org/0000-0001-5480-3421
Taylor Oshan http://orcid.org/0000-0002-0537-2941
Sergio Rey http://orcid.org/0000-0001-5857-9762
Francisco Rowe http://orcid.org/0000-0003-4137-0246
Seda Şalap-Ayça http://orcid.org/0000-0002-5788-9563
Seth Spielman http://orcid.org/0000-0002-5089-7632

Data and codes availability statement

This manuscript involves no data or codes.

References

Akbari, K., Winter, S., and Tomko, M., 2023. Spatial causality: a systematic review on spatial causal inference. *Geographical Analysis*, 55 (1), 56–89.

Alessandretti, L., 2022. What human mobility data tell us about COVID-19 spread. *Nature Reviews. Physics*, 4 (1), 12–13.

Alikhademi, K., *et al.*, 2022. A review of predictive policing from the perspective of fairness. *Artificial Intelligence and Law*, 30 (1), 1–17.

Allen, C., and Mehler, D.M.A., 2019. Open science challenges, benefits and tips in early career and beyond. *PLoS Biology*, 17 (5), e3000246.

Arribas-Bel, D., *et al.*, 2021. Open data products-A framework for creating valuable analysis ready data. *Journal of Geographical Systems*, 23 (4), 497–514.

Bardin, S., and Kedron, P., 2022. A Geographic Perspective on Place-Based Policies. In *2022 APPAM Fall Research Conference*. APPAM https://peterkedron.com/s/Bardin_Kedron_APPAM-Working-Paper.pdf.

Bernard, R.E., and Cooperdock, E.H.G., 2018. No progress on diversity in 40 years. *Nature Geoscience*, 11 (5), 292–295.

Binder, C.R., *et al.*, 2013. Comparison of frameworks for analyzing social-ecological systems. *Ecology and Society*, 18 (4), 26. http://www.jstor.org/stable/26269404.

Binz, C., and Truffer, B., 2017. Global Innovation Systems—a conceptual framework for innovation dynamics in transnational contexts. *Research Policy*, 46 (7), 1284–1298.
Boeing, G., 2020. The right tools for the job: The case for spatial science tool-building. *Transactions in GIS*, 24 (5), 1299–1314.
Brooks, {t., *et al.*, 2024. }. *Video generation models as world simulators*. OpenAI. https://openai.com/research/video-generation-models-as-world-simulators (last accessed 5 April 2024).
Brown, G., and Kyttä, M., 2014. Key issues and research priorities for public participation GIS (PPGIS): a synthesis based on empirical research. *Applied Geography*, 46, 122–136.
De Winne, J., and Peersman, G., 2021. The adverse consequences of global harvest and weather disruptions on economic activity. *Nature Climate Change*, 11 (8), 665–672.
Dutta, M., *et al.*, 2021. Decolonizing open science: Southern interventions. *Journal of communication*, 71 (5), 803–826.
Franklin, R.S., *et al.*, 2021. Who counts? Gender, gatekeeping, and quantitative human geography. *The Professional Geographer*, 73 (1), 48–61.
Franklin, R.S., *et al.*, 2023. Making space in geographical analysis. *Geographical Analysis*, 55 (2), 325–341.
Gahegan, M., 2023. From reproducible to explainable GIScience (short paper). *GIScience and Remote Sensing*, 32, 1–32.
Gao, B., *et al.*, 2022. Causal inference in spatial statistics. *Spatial Statistics*, 50, 100621.
Gao, S., *et al.*, 2020. Association of mobile phone location data indications of travel and stay-at-home mandates with COVID-19 infection rates in the US. *JAMA Network Open*, 3 (9), e2020485.
Gibbons, S., and Overman, H.G., 2012. Mostly pointless spatial econometrics?*. *Journal of Regional Science*, 52 (2), 172–191.
Goodchild, M.F., and Haining, R.P., 2004. GIS and spatial data analysis: converging perspectives. *Papers in Regional Science*, 83 (1), 363–385.
Gurnee, W., and Tegmark, M., 2023. Language models represent space and time. arXiv [cs.LG]. http://arxiv.org/abs/2310.02207.
Haines-Young, R., Green, D.R., and Cousins, S.H., 2003. *Landscape ecology and geographical information systems*. London: CRC Press.
Harvey, D., 1969. *Explanation in geography*. London: Edward Arnold.
Henderson, J., *et al.*, 2002. Global production networks and the analysis of economic development. *Review of International Political Economy*, 9 (3), 436–464.
Herrera Gómez, M., Ruiz Marín, M., and Mur Lacambra, J., 2014. Testing spatial causality in cross-section data. https://mpra.ub.uni-muenchen.de/56678/1/MPRA_paper_56678.pdf (last accessed 29 July 2024).
Hoffman, T.D., and Kedron, P., 2023. Controlling for spatial confounding and spatial interference in causal inference: modelling insights from a computational experiment. *Annals of GIS*, 29 (4), 517–527. https://www.tandfonline.com/doi/abs/10.1080/19475683.2023.2257788 (last accessed 29 July 2024).
Huang, W., 2022. What were GIScience scholars interested in during the past decades? *Journal of Geovisualization and Spatial Analysis*, 6 (1), 7.
Janowicz, K., *et al.*, 2020. GeoAI: spatially explicit artificial intelligence techniques for geographic knowledge discovery and beyond. *International Journal of Geographical Information Science*, 34 (4), 625–636.
Kang, Y., *et al.*, 2020. Multiscale dynamic human mobility flow dataset in the U.S. during the COVID-19 epidemic. *Scientific Data*, 7 (1), 390.
Kattenborn, T., *et al.*, 2021. Review on Convolutional Neural Networks (CNN) in vegetation remote sensing. *ISPRS Journal of Photogrammetry and Remote Sensing*, 173, 24–49.
Kawa, N.C., *et al.*, 2021. Training wicked scientists for a world of wicked problems. *Humanities and Social Sciences Communications*, 8 (1), 1–4.
Kedron, P., *et al.*, 2021. Reproducibility and replicability in geographical analysis. *Geographical Analysis*, 53 (1), 135–147.

Kedron, P., *et al.*, 2021. Reproducibility and replicability: opportunities and challenges for geospatial research. *International Journal of Geographical Information Science*, 35 (3), 427–445.
Kedron, P., *et al.*, 2022. Using the specification curve to teach spatial data analysis and explore geographic uncertainties. *Journal of Geography in Higher Education*, 46 (2), 304–314.
Kedron, P., *et al.*, 2024. A framework for moving beyond computational reproducibility: Lessons from three reproductions of geographical analyses of COVID-19. *Geographical Analysis*, 56 (1), 163–184.
Kedron, P., Holler, J., and Bardin, S., 2023. Reproducible research practices and barriers to reproducible research in geography: insights from a survey. *Annals of the American Association of Geographers*, 114 (2), 1–18.
Koerber, A., Ardon-Dryer, K., and Starkey, J.C., 2023. *The predatory paradox: ethics, politics, and practices in contemporary scholarly publishing*. Cambridge, UK: Open Book Publishers.
Kolak, M., and Anselin, L., 2019. A spatial perspective on the econometrics of program evaluation. *International Regional Science Review*, 43 (1-2), 128–153. https://journals.sagepub.com/doi/10.1177/0160017619869781 (last accessed 29 July 2024).
Kolak, M., *et al.*, 2021. The US COVID Atlas: a dynamic cyberinfrastructure surveillance system for interactive exploration of the pandemic. *Transactions in GIS: TG*, 25 (4), 1741–1765. Jr.
Lawson, V.A., 2004. *Diversifying geography*. Los Angeles, CA: AAG Newsletter.
Li, B., 2022. *Prospects on causal inferences in GIS*. Singapore: New Thinking in GIScience, 109–118.
Li, W., Hsu, C.-Y., and Hu, M., 2021. Tobler's First Law in GeoAI: a spatially explicit deep learning model for terrain feature detection under weak supervision. *Annals of the Association of American Geographers. Association of American Geographers*, 111 (7), 1887–1905.
Manson, S.M., 2023. *Data science and human-environment systems*. United Kingdom: Cambridge University Press.
Markham, K., *et al.*, 2023. A review of methods for scaling remotely sensed data for spatial pattern analysis. *Landscape Ecology*, 38 (3), 619–635.
Michels, A.C., *et al.*, 2024. CyberGIS-compute: middleware for democratizing scalable geocomputation. *SoftwareX*, 26, 101691.
Miller, H.J., and Goodchild, M.F., 2015. Data-driven geography. *GeoJournal*, 80 (4), 449–461.
Miolane, N., *et al.*, 2020. Geomstats: A Python Package for Riemannian Geometry in Machine Learning. *Journal of Machine Learning Research: JMLR*, 21 (223), 1–9.
Morgan, S.L., and Winship, C., 2007. *Counterfactuals and causal inference: methods and principles for social research*. New York: Cambridge University Press.
Munafò, M.R., *et al.*, 2017. A manifesto for reproducible science. *Nature Human Behaviour*, 1 (1), 0021.
Nelson, T.A., Goodchild, M.F., and Wright, D.J., 2022. Accelerating ethics, empathy, and equity in geographic information science. *Proceedings of the National Academy of Sciences of the United States of America*, 119 (19), e2119967119.
Noi, E., Rudolph, A., and Dodge, S., 2022. Assessing COVID-induced changes in spatiotemporal structure of mobility in the United States in 2020: a multi-source analytical framework. *International Journal of Geographical Information Science*, 36 (3), 585–616.
Olivera, P., *et al.*, 2019. Big data in IBD: a look into the future. *Nature Reviews. Gastroenterology and Hepatology*, 16 (5), 312–321.
Openshaw, S., and Openshaw, C., 1997. *Artificial intelligence in geography*. New York: John Wiley & Sons Inc.
Oshan, T.M., *et al.*, 2022. A scoping review on the multiplicity of scale in spatial analysis. *Journal of Geographical Systems*, 24 (3), 293–324.
Pickles, J., 1991. Geography, GIS, and the surveillant society. *Papers and Proceedings of Applied Geography*, 14 (8), 80–91.
Reich, B.J., *et al.*, 2021. A review of spatial causal inference methods for environmental and epidemiological applications. *International Statistical Review = Revue Internationale de Statistique*, 89 (3), 605–634.
Rey, S.J., 2009. Show me the code: spatial analysis and open source. *Journal of Geographical Systems*, 11 (2), 191–207.

Rey, S.J., 2023. Big code. *Geographical Analysis*, 55 (2), 211–224.
Richardson, D.B., *et al.*, 2015. Replication of scientific research: addressing geoprivacy, confidentiality, and data sharing challenges in geospatial research. *Annals of GIS*, 21 (2), 101–110.
Rowe, F., 2023. Big data. *In:* L. Lees and D. Demeritt, eds. *Concise encyclopedia of human geography*. Liverpool, UK: Edward Elgar Publishing, 42–47.
Rowe, F., *et al.*, 2020. The potential of notebooks for scientific publication: Reproducibility, and dissemination. *REGION*, 7 (3), E1–E5.
Rowe, F., *et al.*, 2023. Urban exodus? Understanding human mobility in Britain during the COVID-19 pandemic using Meta-Facebook data. *Population, Space and Place*, 29 (1), e2637.
Şalap-Ayça, S., and Jankowski, P., 2016. Integrating local multi-criteria evaluation with spatially explicit uncertainty-sensitivity analysis. *Spatial Cognition and Computation*, 16 (2), 106–132.
Singleton, A.D., and Spielman, S., 2024. Segmentation using large language models: A new typology of American neighborhoods. *EPJ Data Science*, 13 (1), 34.
Smith, T.R., 1984. Artificial intelligence and its applicability to geographical problem solving. *The Professional Geographer*, 36 (2), 147–158.
Stengers, I., 2016. "Another Science Is Possible!": A Plea for Slow Science. *In*: *Demo(s)*. Leiden, The Netherlands: Brill, 53–70.
Sundstrom, S.M., *et al.*, 2023. Panarchy theory for convergence. *Sustainability Science*, 18 (4), 1–16.
Tollefson, J., 2019. Humans are driving one million species to extinction. *Nature*, 569 (7755), 171–171.
Turton, I., and Openshaw, S., 1998. High-performance computing and geography: developments, issues, and case studies. *Environment and Planning A: Economy and Space*, 30 (10), 1839–1856.
UNESCO 2023. *Engaging societal actors in open science*. https://unesdoc.unesco.org/ark:/48223/pf0000386813 (last accessed 4 April 2024).
US Census Bureau 2015. Item Allocation Rates. https://www.census.gov/acs/www/methodology/sample-size-and-data-quality/item-allocation-rates/ (last accessed 30 April 2024).
Wagenmakers, E.-J., *et al.*, 2011. Why psychologists must change the way they analyze their data: the case of psi: comment on Bem (2011). *Journal of Personality and Social Psychology*, 100 (3), 426–432.
Wang, Y., *et al.*, 2022. Understanding internal migration in the UK before and during the COVID-19 pandemic using twitter data. *Urban Informatics*, 1 (1), 15.
Wellenius, G.A., *et al.*, 2021. Impacts of social distancing policies on mobility and COVID-19 case growth in the US. *Nature Communications*, 12 (1), 3118.
Winter, S., *et al.*, 2024. The challenge of data analytics with climate-neutral urban mobility (Vision Paper). *ACM Transactions on Spatial Algorithms and Systems*, 10 (2), 1–10.
Wu, J., and David, J.L., 2002. A spatially explicit hierarchical approach to modeling complex ecological systems: theory and applications. *Ecological Modelling*, 153 (1-2), 7–26.
Xin, Y., *et al.*, 2022. Vision paper: causal inference for interpretable and robust machine learning in mobility analysis. In *SIGSPATIAL '22: Proceedings of the 30th International Conference on Advances in Geographic Information Systems*, 1–4.
Yeung, H.W.-C., 2023. *Theory and explanation in geography.* London: Wiley.
Yu, Z., *et al.*, 2021. Disruption in global supply chain and socio-economic shocks: a lesson from COVID-19 for sustainable production and consumption. *Operations Management Research*, 15 (1-2), 233–248.
Zhang, J., and Wolf, L.J., 2024. Rethinking "causality" in quantitative human geography. *Geography Compass*, 18 (3), e12743.
Zhao, B., and Feng, J., 2024. A humanistic future of GeoAI. In *Handbook of Geospatial Artificial Intelligence*, 406–410. Seattle, Washington: CRC Press.
Zhao, B., *et al.*, 2021. Deep fake geography? When geospatial data encounter artificial intelligence. *Cartography and Geographic Information Science*, 48 (4), 338–352.