Cartography and Geographic Information Science

ISSN: 1523-0406 (Print) 1545-0465 (Online) Journal homepage: www.tandfonline.com/journals/tcag20

Tool, toolmaker, and scientist: case study experiences using GIS in interdisciplinary research

B. A. Ricker, P. R. Rickles, G. A. Fagg & M. E. Haklay

CARTOGRAPHY AND GEOGRAPHIC INFORMATION SCIENCE
2020, VOL. 47, NO. 4, 350–366
https://doi.org/10.1080/15230406.2020.1748113

ARTICLE

OPEN ACCESS

Tool, toolmaker, and scientist: case study experiences using GIS in interdisciplinary research

B. A. Ricker[a], P. R. Rickles[b], G. A. Fagg[b] and M. E. Haklay[c]

[a]Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, The Netherlands; [b]Department of Civil, Environmental, and Geomatic Engineering, University College London, London, UK; [c]Department of Geography, University College London, London, UK

ABSTRACT

Geographic Information Systems (GIS) are valuable for displaying and analyzing spatial data, revealing spatial patterns that may otherwise go unnoticed. The ubiquity of web and mobile platforms, used to create and share geographic information has reified the value of GIS to a wider audience bringing new popularity to GIS. As a result, GIS and Geographic Information Science (GIScience) are becoming increasingly sought after in interdisciplinary research, which often addresses multifaceted, real-world problems. To understand the necessary level of GIS expertise for a specific interdisciplinary research project, we suggest that the team early on identify the role of GIS within the research. Is it simply the use of GIS as a Tool, employing a GIS Toolmaker for bespoke applications or a GIScientist for new forms of spatial analyses and guidance on social, ethical and spatial ambiguities? To allay future challenges and miscommunication in interdisciplinary research involving GIS, three case studies are presented and common themes related to challenges for the GIScientists are shared.

ARTICLE HISTORY

Received 06 August 2019
Accepted 24 March 2020

KEYWORDS

Interdisciplinary research; geographic information science; spatial turn; Science-technology-society; webgis

1. Introduction

Everything happens somewhere and Geography is the stage on which all-natural and human activity occur (Lawrence, 2008). Spatial data about events are required to construct maps, which are increasingly being made using Geographic Information Systems (GIS). These are systems that can capture, store, analyze, manage and present data that are linked to geographical locations (Bhat et al., 2011). The scientific study of topics associated with geographic information and advancing the analysis thereof is Geographic Information Science (GIScience) (Longley et al., 2010), with associated researchers referred to as Geographic Information Scientists (GIScientists). Traditionally, even use of GIS as a tool required highly trained professionals. However, as geospatial technologies have advanced and become progressively easier to use and more accessible, its value is more obvious to researchers across disciplines (Gouveia & Fonseca, 2008; Paul & Dredze, 2011; Schuurman et al., 2011; Sui & Goodchild, 2011). New web-based and mobile GIS have made geospatial analytical functionality accessible to non-experts and experts alike (Elwood, 2010; Ricker, 2017; Sieber et al., 2016), where a GIS Toolmaker would build such applications. Within the span of a decade from Google Earth's release in 2005, mobile computing devices and sensors became so affordable that even modest research budgets could utilize them at scale (Elwood & Leszczynski, 2013; Kitchin, 2014).

Some see these technological and societal advances as an opportunity for GIScience and GIS to promote spatial thinking, referred to as the "spatial turn" (Cinnamon & Schuurman, 2013; Sui, 2008a, 2008b; Warf & Arias, 2009a, 2009b). However, outputs from GIS should not be so easily accepted without questioning who produced it and their purposes for doing so (Sheppard, 2005). It must be recognized that geographic information can and does influence society, just as society influences the direction of application and development of applied GIS (Chrisman, 2005), for which GIScientists must accept responsibility. Such concepts are based on the reflexive social nature of technologies, which is a core tenet of Science, Technology, and Society (STS).

The benefits of interdisciplinary research, which is research that involves two or more disciplines, has been recognized by many organizations (Baerwald, 2010; National Academy of Sciences, National Academy of Engineering and Institute of Medicine, 2004; National Science Foundation, n.d.). The use of GIS within interdisciplinary research can help solve real-world problems (Kuhn, 2012; The Role of Geospatial Information in the Sustainable Development Goals, 2015). The interdisciplinary nature of GIScience and GIS makes both conducive to such research.

CONTACT B. A. Ricker b.a.ricker@uu.nl

This article has been republished with minor changes. These changes do not impact the academic content of the article.

Though offering multiple perspectives, interdisciplinary research can be complex and multifaceted (Golding, 2009; Rickles & Ellul, 2014). GIScientists in interdisciplinary projects are often responsible for learning and implementing skills outside of their own expertise. This is apparent in initiatives that bring together those from different disciplines where methods must quickly shift to accommodate research aims, which often evolve as a project is underway. They must also be sensitive to the social implications of their work while ensuring they have the necessary technological expertise to add value to the project.

Here, we define the use of GIS as a tool, the need for a GIS Toolmaker or a GIScientist within interdisciplinary research. While we recognize that all GIS researchers need to be flexible in projects to resolve challenges, sometimes the tool versus science debate is counterproductive. Here we argue that describing these differences to interdisciplinary research teams at the onset of a project could help set clear goals and identify a best fit GIS expert for an interdisciplinary research project. Even though the ideas shared here will be familiar to seasoned GIScientists, we see value in formally documenting and sharing them. Our aim is to make recommendations for those embarking on interdisciplinary research, to delineate the role of GIS and for those applying it, to acknowledge their responsibility to not only have the necessary level of expertise in GIS, but to also learn about other disciplines and deliver on the agreed goals. Our approach to learning external disciplinary methodologies as well as educating researchers about our own is rooted in social constructivism, which centers on the social, intersubjective nature of knowledge creation (Au, 1998) and is regularly utilized in GIS education (Milson & Earle, 2008). Three interdisciplinary research cases are presented and each of the projects were funded for their interdisciplinary nature and included a section about the contribution to GIScience literature, justifying the need for a GIScientist instead of simply using GIS as a tool. Based on our experiences in interdisciplinary research projects from the three cases, we offer common themes that emerged which are 1) advocate for your discipline, 2) consequences for too much or too little focus on your discipline, 3) go beyond your discipline, and 4) benefits, but also limitations, to collaboration.

Here, we first present a literature review including a contextualization of the current use of GIS and STS. We then look at the inter-relatedness of GIS and interdisciplinary research, what GIScience has to offer and challenges associated with GIS application in such projects. Afterward, we share how to select the level of GIS expertise needed for interdisciplinary research (GIS as a tool, GIS Toolmaker, GIScientist) based on the project's needs. Next, we present three case studies that describe successes and failures regarding the researchers' experiences of applying GIS in interdisciplinary research. Common themes that emerged from observations in the case studies, as related to the literature, are then explored. We then present a discussion and conclusion summarizing key findings.

These shared experiences highlight the complex role of GIScience and interdisciplinary understandings and provide a reflection on what all researchers may need to consider before, during and after a project to best meet the multi-faceted needs of interdisciplinary research. Though relevant to researchers from various disciplines, this paper is intended to provide GIScientists insight and provoke reflection within interdisciplinary research so that future projects may apply these lessons learned.

2. Background

Geospatial technologies are weaving themselves into everyday life (i.e. weather, directions, and traffic apps), rendering the technologies both ubiquitous and invisible. People, including researchers outside the domain of GIScience, are increasingly taking geospatial technologies for granted, not recognizing the complexity, ethical implications and social impact. It is necessary to understand technical as well as non-technical challenges with GIS for successful implementation and effective utilization. Such applications will also vary based upon the project's GIS needs, whether it uses GIS as a tool, requires a GIS Toolmaker or a GIScientist. This highlights the ongoing debate from within Geography and GIScience on whether GIS is a tool or a science. We acknowledge this, as it is still relevant to consider regarding the use of GIS in interdisciplinary research and beyond (Goodchild, 2004; Mark, 2003); and are extensively covered in other literature (Mark, 2003; Wright et al., 1997).

2.1. Modern GIS and science & technology studies

The creation of technologies such as Google Maps and Google Earth meant that anyone with an internet connection gained access to basic tools associated with GIS (Elwood et al., 2012; Goodchild, 2007a, 2007b, 2009; Graham & Zook, 2011; Rana & Joliveau, 2009; Sui, 2008a, 2008b; Turner, 2006). Previously, the ability to overlay vector data (e.g., roads) on top of raster data (e.g., satellite imagery) to document and make decisions was reserved for GIScientists or those with access to and understanding of expensive and difficult to use tools. Now, digital globes allow a general user to "fly" anywhere in the world through the availability of aerial imagery of every place (Goodchild, 2007a, 2007b; Turner, 2006).

Digital apps with maps are easily available via web and mobile platforms. 2.6 billion people globally are estimated to own smartphones (Holst, 2018) and with 5 billion requests per week to Apple Maps alone in 2015 (Elmer-DeWitt, 2015), it is clear that there is a large market for users of geospatial data. Sui and Goodchild (2001) predicted this proliferation of GIS, and then confirmed and reflected on the role of GIS as media (Sui & Goodchild, 2011). This supports the suggestion that the ubiquity of web and mobile location-based services will increasingly affect how geographic information is created and/or used (Rouse et al., 2007).

This is particularly exciting for scientists who aim to collect data in large geographic areas. Digital globes, when combined with location-aware sensing devices, enable knowledgeable local experts and citizens to contribute spatial data (Connors et al., 2012). This has significant promise for citizen science, inviting the public to help collect data to augment existing scientific efforts (Connors et al., 2012; Haklay, 2017; See et al., 2016; Wiersma, 2010). As potential opportunities and applications for GIS grow, GIScientists must, in turn, develop tools and skills to support citizens from an expanding user base with varying levels of experience and different requirements.

Not only for citizen scientists, but support must also be given to interdisciplinary researchers who wish to use GIS. Indeed, interdisciplinary research projects using geospatial technologies may be undertaken by a myriad of disciplines. Examples include Environmental Scientists analyzing squirrel habitats (Pereira & Itami, 1991), Epidemiologists outlining how to use it for disease studies (Kirby et al., 2017; Nuckols et al., 2004) and Mathematicians harvesting Tweets for mapping sentiment and demographic information (Mitchell et al., 2013). These examples do not present an exhaustive list of interdisciplinary research that utilizes GIS but rather emphasizes the diverse range of topics that GIS has been used to address. The ubiquity of location information has led more researchers from subject areas that traditionally have not examined geographical aspects to increasingly embrace GIS.

While GIS technologies are more contemporarily accessible, it is important to carefully consider their application. Critical GIS is an area of interest that reminds researchers not to simply accept outputs at face value and question the underlying implications of the data, system, analyses, etc. (Sheppard, 2005). Rightly or wrongly, GIS users will adapt it to meet their needs, which allows them to represent the world in a particular way (Sheppard, 2005). GIS and geographic information may be considered boundary objects that embody disciplinary perspectives that can and do change (Harvey & Chrisman, 1998). These perspectives communicated through GIS can and do influence society and vice versa and insights from science studies, such as STS, recognize that technological applications cannot be divorced from the practices of those utilizing them (Pickering, 1995). Technological artifacts, such as GIS, are inseparable from human activity and can stabilize or destabilize social relationships (Harvey & Chrisman, 1998, 2004). The use of GIS when applied in interdisciplinary research will be negotiated through social relationships, which underpins the development of science and technology (Bloor, 1976; Collins, 1981) as well as the content of geographic information (Chrisman, 2005). Some disciplines are more flexible than others with regard using social technologies (Chrisman, 2005). Data created through these technologies and shared between disciplines requires negotiation and mutual alignment, which is not only difficult but also rarely leads to complete agreement (Chrisman, 2005; Poore & Chrisman, 2006). GIS has been recognized for its ability to link social groups and perspectives – even opposing ones (Harvey & Chrisman, 1998). Considering this, it is important to include users in co-construction of a GIS, as social concerns are fundamental to its design (Chrisman, 2005; Poore & Chrisman, 2006). Involving them can help GIScientists avoid technological determinism, which considers technology to have its own momentum without influence from political, economic or social goals (Harvey & Chrisman, 2004).

2.2. Interdisciplinary research and GIScience

GIScience and GIS have both been long been considered interdisciplinary areas for research. The term interdisciplinary research in a broad sense " … means between disciplines, suggesting the basic elements of at least two collaborators, at least two disciplines, and a commitment to work together in some fashion in some domain" (Stember, 1991, p. 4). This type of research has been said to have been " … inspired by the drive to solve complex questions and problems, whether generated by scientific curiosity or by society … " and has led " … researchers in different disciplines to meet at the interfaces and frontiers of those disciplines and even … form new disciplines." (National Academy of Sciences, National Academy of Engineering and Institute of Medicine, 2004, p. 16). Another factor of interdisciplinary research is that it is " … more oriented to addressing real-world problems than is disciplinary research, which often focuses more on basic theoretical understandings than on practical applications." (Baerwald, 2010, pp. 495–496).

Geography is considered interdisciplinary itself (Baerwald, 2010) and as such complementary to interdisciplinary research for its ability to absorb ideas and techniques from neighboring intellectual territories (Becher & Trowler, 2001), while also lending its tools and methodologies to other subjects (Clawson & Johnson, 2004). GIScience has also been described as an interdisciplinary field with a broad range of valuable contributions across disciplines (Blaschke & Merschdorf, 2014). Methodologies from GIScience around housing and analyzing robust spatial data and the ability to apply geographic information across disciplines to solve societal problems has allowed GIS to transcend boundaries and provide symbiotic benefit (Blaschke & Merschdorf, 2014; Dibiase et al., 2007; Kuhn, 2012; Reitsma, 2013). This not only demonstrates how GIS may be conducive for interdisciplinary work, but how it is a fundamental tool for research (Chen, 1998).

The National Science Foundation (NSF) states that it " … has long recognized the value of interdisciplinary research in pushing fields forward and accelerating scientific discovery. Important research ideas often transcend the scope of a single discipline or program." (National Science Foundation, n.d.). The National Academy of Sciences, National Academy of Engineering and the Institute of Medicine (National Academy of Sciences, National Academy of Engineering and Institute of Medicine, 2004) also acknowledge the importance of interdisciplinary research as a productive and inspiring pursuit, which has already delivered much and promises more. Academic institutions reflexively are undertaking and prioritizing interdisciplinary research as " … a necessary response to intensifying demands that research should become more integrated than before with society and the economy … " (Barry & Born, 2013, p. 4). GIS and GIScience applied in interdisciplinary research also have important roles. Kuhn (2012) posits that spatial information at global, regional and local scales is essential for addressing biodiversity, climate change, cultural heritage, debt, energy, water, natural hazards, health, poverty and security. This is also reflected in the seventeen United Nations Sustainable Development Goals, where GIS could be used to analyze data for example, with Goal 1: End Poverty (land ownership, natural resources, workforce productivity, etc.), Goal 3: Good Health and Well-Being (crimes, disease outbreaks, accessibility of health services, etc.) and Goal 13: Climate Action (profile of land, hazards, exposure, etc.) (The Role of Geospatial Information in the Sustainable Development Goals, 2015). Widespread uptake of spatial analysis across disciplines to address these challenges and more is seen as a renaissance in geography (Warf & Arias, 2009a, 2009b). With new users from different disciplines using GIS, this is an opportunity for increased diversity and potential for more and varied applications to meet the needs of this increasingly heterogeneous population. Soja (2009) has gone so far as to claim that this increased spatial perspective is the most significant intellectual and political advancement of the 21st century.

Using interdisciplinary research that incorporates analyses from multiple perspectives can help with deriving sustainable solutions to solve globally relevant challenges (Johannes & Kasteren, 1996). However, such solutions must also include diverse social information to be innovative, thriving applications (Poore & Chrisman, 2006). Indeed, for GIS to be successfully integrated within interdisciplinary research projects, it will have to have " … a broad understanding of the uniqueness and unity of a place, not just the components of a system representing the place." (Harvey, 1997, p. 83). As GIS has made it easier for people to create and investigate geographic information, it may also create conditions for disastrous applications due to amateur users' inadequate understanding of the technology and related spatial science issues (Openshaw, 1993). Critical GIS literature highlights issues around "limits to GIS representations of the world; limits in access to and the appropriateness of GIS technologies; legal and ethical implications of GIS use; and the applicability of GIS for redressing social and geographical inequalities." (Sheppard, 2005, p. 8). The power and agenda of the agencies compiling, analyzing and producing the outputs and who may positively or negatively be benefitted by this process must also be taken into consideration (Sheppard, 2005). There are also further issues that can arise in interdisciplinary research around disciplinary misunderstandings, time constraint issues and communication difficulties (Rickles & Ellul, 2014). Such challenges are particularly well known within GIScience (Blaschke & Merschdorf, 2014). Though there can be many hurdles to interdisciplinary research, with the right approach, problems may be avoided early on, increasing the probability of the project being successful. Solutions may include building relationships, getting training in new frameworks/methodologies, and having clear management goals (Rickles & Ellul, 2014). Often overlooked as well is the need for researchers, particularly GIScientists, to have excellent communication, business/project management, and/or team working skills – skills that have been identified as lacking in graduates from tertiary education (Schulz, 2008).

GIS poses further technical challenges as those who wish to use it will require knowledge of appropriate procedures for representing the world, gathering, managing, analyzing and visualizing spatial data (Blaschke & Merschdorf, 2014; Reitsma, 2013). It is also questionable as to the level of background knowledge one coming from outside of GIScience would need to acquire to successfully understand abstract spatial representation, associated issues (e.g., the Modifiable Areal Unit Problem, where different aggregations of spatial data can affect results) and ethical implications. Where time or other factors mean including such concepts are not feasible or necessary, projects can still make use of GIS as a tool. Technical skills are also needed for the effective application of GIScience principles. Outside of specific disciplinary knowledge, to create and customize GIS web and mobile applications, researchers need to develop fundamental computer science and programming skills, which are deemed essential for proficient GIS practitioners (Dramowicz et al., 1993; J. Johnson, 2010; Lui et al., 2012; Wright et al., 1997). This can include skills and knowledge in, but not limited to: Python, JavaScript, Structured Query Language (SQL), Hyper-text Markup Language (HTML) and Cascading Style Sheets (CSS) (Bowlick et al., 2017) which could be considered relevant for toolmaking, and need updating as technology evolves.

2.3. Geographic information: tool, toolmaker, scientist

Couclelis (2012) highlighted that defining GIScience is a more complex challenge than naming it because the field itself is continually evolving and morphing. What is and is not GIScience has also long been debated (Mark, 2003; Wright et al., 1997). Here, we do not intend to overly simplify this debate, nor do we wish to provide a philosophical warrant for the foundational question "what is science?". However, this should be discussed early and often among interdisciplinary research teams, as GIS can be applied as both tool and science in interdisciplinary work. Regardless, an initial assessment should be done to decide team composition and to employ researchers who have the necessary skills to achieve the intended goals of a project.

To ascertain the level of GIS aptitude needed to deliver agreed outputs, is necessary to understand and define them. As GIScientists, we recognize that there are significant differences between the simple use of a software package (GIS as a Tool), making bespoke solutions (GIS Toolmaker) and acquisition of in-depth, scientific knowledge (GIScientist). People can learn about GIS and related concepts either through informal (learning by experience with no set learning objectives), non-formal (short courses or seminars as part of adult learning) or formal (undergraduate/graduate education with set learning objectives) education (Organisation for Economic Co-operation and Development/Organisation de Cooperation et de Development Economiques (OECD), n.d.). The route pursued often depends on the depth of expertise the learner wishes to obtain to apply their understanding to achieve their goals, with those who wish to be GIScientists often undertaking formal education.

Regarding the breadth of acquired knowledge of GIS, inspired by Huxhold (2000) and A. Johnson (2006), we have defined different classes of GIS experts are as follows and illustrated their hierarchy in Figure 1:

- GIS Tool User: defined as "light" and "heavy" both will use GIS, where the latter will do so more frequently, and both will be able to navigate around the system to perform basic tasks, acquiring more knowledge over time. Exposure to GIS maybe through a web-based client-side portal. Other tool users include GIS Technicians who may only do simple data entry on the job, while GIS Analysts are responsible for undertaking data analyses, integration and conversion, manage products and systems and can coordinate work tasks and activities.
- GIS Toolmaker: This includes GIS Specialists who design, develop, customize and maintain discipline specific GIS.
- GIScientists: may be considered as those who are able to do most elements from the above-mentioned roles in addition to understanding the conceptual and theoretical implications of the work to be undertaken. GIScientists will have advanced knowledge of existing methods and understand social and ethical considerations of implementation. They will aim " … to minimize

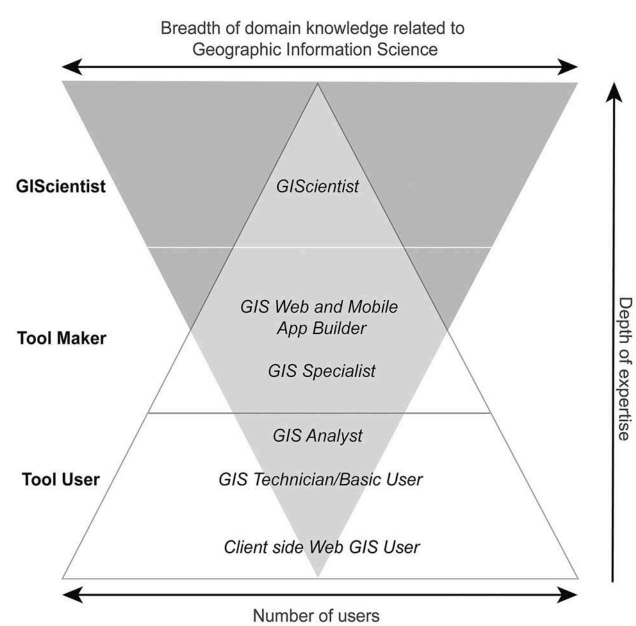

Figure 1. Breadth and depth of knowledge for GIS as a tool versus a science and examples of different job classifications for each level. These boundaries are not firm.

the uncertainty added during information create and to involve uncertainty explicitly at each stage in the geographic information life cycle so that the domain user has a fully informed understanding of the situation." (Roth, 2009, p. 317).

It should be recognized that within these levels of GIS expertise, the relevant job classes have varying abilities in GIS. A GIS Technician may be presumed to have more GIS expertise than a Basic User or "Virtual" User and a Programmer/Engineer/Developer to have more than a Specialist or Analyst. Regardless of whether a GIScientist has proficiency in another area (e.g., Computational, Social, Physical, etc. GIScientist), for simplicity, they will simply be considered to be a GIScientist.

These levels of GIS expertise (GIS as a Tool, GIS Toolmaker, GIScientist) may then be used as part of the initial interdisciplinary research evaluation process. Indeed, "Effective interdisciplinary research demands a greater understanding of the methods and outcomes of different disciplinary components of the research program, to work out how they relate to one another and how they should be combined to deliver an overall integrated outcome." (Bruce et al., 2004, p. 467). If GIS is to be part of the project, it should be included in the earliest planning stages and not added as an afterthought. The level and complexity of application may be considered through the dimensions of disciplinary grounding, advancement through integration and critical awareness (Boix Mansilla & Dawes Duraisingh, 2007). Though initially applied to evaluating students' interdisciplinary work, this may also be applied to interdisciplinary research. The disciplinary grounding or expertise of a researcher and willingness for interdisciplinary collaboration have both been identified as being important for the success of the interdisciplinary project. In one study that interviewed 20 researchers with experience in "mixed-methods", many interviewees expressed concerns that researchers that had been employed on the project " … might not have the skills to do one component to a high enough standard – or indeed either component – or funding might not be available to recruit two researchers of a suitable standard." (O'Cathain et al., 2008, p. 1579).

It is necessary to assess these details to successfully plan for and deliver interdisciplinary outputs with GIS and avoid difficult situations. The following are some examples of situations to consider in interdisciplinary research involving GIS:

- Tediously creating maps (GIS as a Tool) when a custom solution could do so more efficiently (GIS Toolmaker) or where more complex understanding could make a more enriching and insightful output (GIScientist).
- Trying to build a GIS tool (GIS Toolmaker), when either simple, visual outputs would suffice (GIS as a Tool) or greater conceptual knowledge is necessary for the custom tool to accurately provide appropriate information to the intended target audience (GIScientist).
- Trying to inject GIScience into projects (GIScientist) that only need visuals (GIS as a Tool) or a bespoke application (GIScientist or Toolmaker). For GIScientists, if GIScience is to be applied to an interdisciplinary research project, it can and should provide value and it is the responsibility of the GIScientist to deliver that value.

These concepts of modern GIS applications (and concerns), the value (and challenges) of applying GIS in interdisciplinary research and types of application of GIS in interdisciplinary research projects (GIS as a Tool, GIS Toolmaker, GIScientist), will be further explored through three interdisciplinary research projects described in the next section. The aim is to share our experiences on how the interdisciplinary teams were formed, their sometimes-conflicting goals, how they attempted to circumnavigate problems and their successes in achieving their goals, which evolved over time and with experience.

3. Methods and cases

An idiographic approach was taken to explore the phenomena of three case studies through the observations of some of the researchers that were a part of them (three GIScientists and one Disaster Management Expert with experience using GIS as a Tool). The GIScientists, as well as the other researchers on these projects, all had their own objectives for the use of GIS to create desired disciplinary and interdisciplinary outputs. Some of their agenda may have been complementary to one another, while others were in direct opposition. These relationships may be better understood through Actor-Network Theory (ANT). As defined by Fenwick (2010), "ANT traces the ways in which human and non-human elements are enacted as they become assembled into collectives of activity. These complex, interwoven 'networks' can spread across space and time, and produce policies, knowledge, and practices." (120) Within the case studies, the researchers from the various disciplines may be considered actors that bring their own experiences to the project. The GIS employed may be considered a non-human actor on each of these projects that has agency and influence on the human actors. For example, the direction of research could be influenced by those who are familiar with the software based on the limits of what it permits or can be tweaked to permit (Sheppard, 2005). By understanding how all actors have come together and interacted, it is possible to understand how their actions (or inactions) positively (or negatively) affected the GIS outputs of the associated interdisciplinary research projects.

3.1. Case studies

The three cases shared here vary dramatically in content, context, and scale. An overview of the cases is shared and briefly summarized, in Table 1, by the overarching purpose, those involved in the research, and the GIS project needs, methods employed and outcomes.

The first case was called Adaptable Suburbs and the aim was to use a socio-historical analytical lens to measure the sustainability of four suburban town centers around London. This research team was comprised of Anthropologists, Historians, Architects, and GIScientists. In this project, which ran from 2010 to 2014, there were diverse data needs: Anthropologists wanted to use GIS for their ethnographic collection of data (e.g., local economies, remembered histories, etc.), Historians sought to review changes across time to road networks and businesses by analyzing historic maps, and Architects wished to use GIS as a tool for better understanding connectivity and integration of road networks, patterns in business location and diversity of business types. The GIScientists wanted to implement a metadata system for geospatial data to be used by the project as well as a web GIS for collecting community data to study data sharing activities (both of which required GIS Toolmaking). The former was used to understand accuracy and reliability of project data, engaging with GIScience concepts, and outputs from the latter were analyzed and visualized in GIS to produce maps as outputs (GIS as a tool). Adaptable Suburbs researchers needed GIS and GIScientists to help organize data to make informed decisions and observe phenomena that may otherwise be too complex to see without the data analysis and visualizations produced by GIS.

The second case was an interdisciplinary research project related to the development and evaluation of an Electronic Health Record (EHR) that was originally created for injury surveillance in low-resource settings. This is an on-going project, but the specific sub-project reported here took place in 2012. This research team was comprised of Surgeons, Medical Practitioners, and GIScientists. Surgeon and Medical Professionals were tasked to input patient data related to the location of injury for the GIScientists. Together, they aimed to aggregate the spatial distribution of injury to identify localized injury mitigation efforts. The EHR project was a combination of use of GIS as a tool, GIS Toolmaking, and GIScience, with GIS Toolmaking used to create an app used to collect spatial data, GIS to analyze hot spots of injury and GIScience to research and communicate ambiguities and advise on social and technical implications.

The third case was Challenging RISK, a multifaceted project that took place from 2014 to 2018. The aim of this project was to take a community-driven approach to investigate potential improvements to earthquake and fire preparedness in the Seattle metropolitan region. This interdisciplinary team was comprised of Structural

Table 1. Overview of the three case studies briefly explained.

	Adaptable Suburbs	Electronic Health Record	Challenging RISK
Time Frame	Nov 2010 – Oct 2018	May 2012 – Sep 2012	Jan 2014 – Oct 2018
Purpose	To measure the Sustainability of Suburban Town Centers through a socio-historical analysis of four suburbs in London	Build a mobile data collection tool to capture data at the point of care to then spatially analyze data to identify where injury occurs in an effort to place mitigation measures	Investigate impacts and potential improvements to community earthquake and fire. Disaster preparedness for a household of varying socio-cultural backgrounds
Actors	GIScientists; Anthropologists; Historians; and Architects/Urban Designers	GIScientists; Surgeons; Medical Practitioners	GIScientists; Structural Fire Engineers; Structural Earthquake Engineers; Social Psychologists
GIS Project Needs	Anthropologists wanted to use GIS for ethnographic data collection (e.g., local economies, remembered histories, etc.); Historians wanted to digitize historical maps to document changes to road networks and businesses over time; and Architects/Urban Designers wished to use GIS as a tool for measure connectivity and integration of road networks, patterns in business location and diversity of business types. GIScientists aimed to build a web GIS including a metadata system for geospatial data for collecting community data to study data sharing activities	Spatial data related to where an injury occurred was to be collected at the point of healthcare. GIScientists aimed to use these data to conduct spatial analysis to generate a map to display the distribution of injury, identify clusters or hotspots of injury in an effort to identify injury mitigation efforts	Social Psychologists required their sample of the community to be representative of the entire population of Seattle; both Structural Engineering partners (Fire and Earthquake) were interested in communities with mid-rise buildings (5–6 stories) that were built before the time period of high regulations (1970s and earlier), which may be a more significant risk of collapse. GIScientists wanted to build a WebGIS or mobile app for spatial data collection related to earthquake preparedness

Engineers who specialize in fire and earthquakes, Social Psychologists and GIScientists. Structural Earthquake Engineers were interested in GIS to identify the location and ages of buildings as this relates to building codes associated with policies around seismic retrofitting. Structural Fire Engineers were curious if participants had working smoke detectors and followed typical fire safety procedures. Social Psychologists were interested in identifying socio-demographic information about the population in the region as it relates to disaster preparedness behavior. GIScientists on this project aimed to take a participatory approach to identify and alleviate barriers to disaster preparedness in individual communities and use this information to understand interface usability and spatially relevant patterns. This initially involved creating a custom GIS app (GIS Toolmaking), facilitating public participation in contribution and understanding of geospatial data (GIScience) and visualizing outputs for collaborators from other disciplines and shared publications (GIS as a Tool).

4. Common themes

The common themes that emerged from the different case studies that also relate to the concepts of STS, interdisciplinary research and GIS applications mentioned earlier are: 1) advocate for your discipline, 2) consequences for not championing your discipline, 3) go beyond your discipline, and 4) benefits, but also limitations, to collaboration.

(1) Researchers should advocate for the benefits of their disciplines when applied within interdisciplinary research projects; however, they should not do so naively. It is valuable to step outside of one's own disciplinary perspective to consider the research problem at hand through the lens of another epistemology, being honest and recognizing as well the disbenefits and weaknesses in some of the approaches of GIS and GIScience. It is important to reflect on the role of technology and its social influences on research findings.

(2) Interdisciplinary research is often complex with a lot of activity occurring within and amongst the disciplinary workstreams of the project, so it is important for GIScientists to maintain a balance of delivering against disciplinary and interdisciplinary goals. Researchers may be keen to focus on interdisciplinary outputs; however, GIScientists will struggle to professionally advance within their disciplines if they do not also demonstrate the impact GIS or GIScience had on the project. It can be useful to have senior principal investigators who have interdisciplinary experience and can guide researchers, helping GIScientists in making compromises where necessary and prioritizing work to focus on or deliver.

(3) Going beyond one's discipline to research new and interesting topics can be a fulfilling part of interdisciplinary research. Given the interdisciplinary nature of GIS and GIScience, GIScientists may find it easier to engage in interdisciplinary research than other disciplines find it to learn GIS. GIScientists may need to quickly learn new tools and methodologies for a given project, which they can then incorporate into their own practices, providing benefit to future research. Given the increasing interest in interdisciplinary research, this may also improve job prospects for researchers and open up new opportunities. Some even say that interdisciplinary experience is necessary for career progression (Davé et al., 2016).

(4) As much as there can be benefits to collaboration using GIS and GIScience for interdisciplinary research, the limitations must also be recognized. Building relationships and fostering team spirit on projects can help facilitate communication to work through discrepancies and researchers focus on communal outputs. Such products have the potential of being more than the researchers could accomplish within the bounds of their own discipline, making them novel and innovative. It was acknowledged in one study that publications on interdisciplinary outputs, though not initially as well cited as disciplinary ones, over time are often cited more than disciplinary ones (Van Noorden, 2015). However, counter to the previous theme, interdisciplinary research can make researchers a "jack of all trades and master of none" (Lau & Pasquini, 2008), which may impact future employment.

We turn now to explain how these themes were experienced in the different projects, focusing on how initial goals shifted during each project and how GIScience team members had to adjust.

4.1. Theme 1: advocate for your discipline

Issues arose around conflicts in research agendas in each project, or in lack of understanding related to certain disciplines involved. In the Adaptable Suburbs project, Anthropologists collected material that needed to be handled sensitively, as project researchers were only stewards of the data and participants were the real owners – releasing any contributed information needed their approval beforehand. This was sometimes problematic for geospatial outputs as these data could not be used without specific permission. As such, researchers largely ended up focusing on disciplinary outputs to maximize impact in their respective fields. Eventual lack of interest and understanding about the capabilities of the GIS led to missed opportunities for rich and valuable data collection and analysis. Though there were resulting publications on this work from the project in Anthropology journals, it did not include any GIScience related outputs.

In the EHR project, the GIScientist had to decipher how to best identify where spatial data could be captured in the existing hospital workflow, so that the GIS work could be completed at all. This required the GIScientist to identify ways to improve data capture rates in specific healthcare settings based on existing social structures and access to the technology (which is traditionally a systems engineering challenge and not a GIScience skill). The GIScientist had to reiterate how important it was for everyone to be aware of the data provenance to improve data capture rates.

The disciplinary teams of Challenging RISK started the project in 2014 collaborating closely and with crossover; however, due to methodological variation, researchers quickly began focusing on their own workstreams and individual disciplinary goals, norms, and expectations. For example, where Psychology partners required clearer constraints over what was being shared about the project within the boundaries of their control and intervention neighborhoods, the participatory research methods used by GIScientists posed a potential conflict through the community-based collaboration and information sharing. Thus, it became quickly clear that teams would need to conduct primary research independently, in parallel, rather than together. Similarly, GIScientists were to initially survey buildings or request information from research participants on house construction materials. Engineers were particularly interested in mid/high rise multiple occupancy buildings made of reinforced concrete. It was difficult to find/gather such information or engage with participants in such properties, as most lived in detached houses. This resulted in engineers losing interest in GIScience analyses or outputs.

These were difficult yet important experiences associated with the projects in which individuals from each discipline had to advocate for their individual scholarly expectations and requirements. In EHR and Challenging RISK, the GIScientists were able to effectively do this; however, in Adaptable Suburbs, though GIScience acted as a nexus for the disciplines in project, the GIScientists failed to deliver on their own disciplinary requirements. GIScientists working on interdisciplinary projects must learn to promote the benefits of their discipline. If not, researchers from other disciplines will promote their own methodologies, which may be less effective than ones from GIScience or possibly change the direction of research to the disbenefit of the GIScientists. GIScientists should also concede when GIS tools or analyses are not appropriate and prioritize what is best for the project.

4.2. Theme 2: consequences for too much or too little focus on your discipline

One of the key outputs from Adaptable Suburbs that GIScientists were interested in was the population of geospatial metadata associated with derived data from the project. A system was created to allow researchers to store and maintain data (e.g., documents, GIS files, source data, etc.) that, upon entry, would require the researcher to input necessary metadata (e.g., author, last modified date, quality notes, etc.). Once the system was created researchers agreed and were required by the project senior team of investigators to use the system for all project data and training was given to familiarize researchers with it. However, as time progressed, the system was not used. Follow up workshops were held as well as data entry/metadata population sessions, but researchers still did not sustain the system's use, which may have been due to time constraints or disciplinary priorities (Rickles & Ellul, 2015). Ultimately, geospatial metadata was maintained by the GIScientist and the metadata system's use was abandoned. Though this was one of the main research objectives for GIScientists on the project, due to a lack of outputs, this resulted in a missed opportunity to better understand concepts around spatial metadata.

Within the EHR project, to measure the potential success or challenges associated with the EHR, systematic usability evaluations needed to be conducted. The aim was to test this application with the intended users, namely medical professionals. Since it is difficult to gain access to busy nurses and surgeons, these evaluations were conducted in a less hectic hospital in a Canadian territory and, while medical staff was waiting, with the Mobile Emergency Medical Unit at an Air show. Through the usability evaluations, it became evident that it was uncertain whose responsibility it would be to enter the data required for the decision support tool to offer appropriate and accurate guidance. The geographic data entry process preferred also varied depending on how people described locations in the region. While geographic information was pivotal for the GIScientist to use associated data at all, this field was the least populated since it did not help with the decision support for those entering the data. Though other project aims were met, it was challenging for the GIScientist to derive robust outputs, which made it difficult for subsequent publications and proposals based on this work.

In the case of Challenging RISK and a series of participatory workshops led by the GIScientists, the range of experience and application of the required interdisciplinary skills were particularly demanding for an early career researcher. Challenges included identifying goals of participation and desired output, the logistics of recruiting for and arranging the workshops, communicating effectively with a varied audience, and facilitating productive, community-led discussion, all of which are factors that contribute to difficulty in amalgamating group views and delivering on the community vision. Additionally, this collaborative prototyping and iterative development required rapid design, programming, and feedback collection, with a further need for flexibility in modifying or completely revising the proposed solution based on follow-up community engagement. The process was further complicated by a condensed delivery time frame and, consequently, a fully realized bespoke GIS mobile app prototype was not shared with the original community group. Regardless, the initial parameters derived from this work later reemerged and were implemented using a standard GIS app with a different group. In this project, the researchers ensured there were relevant GIS outputs and did publish some results; however, the other project partners focused on their own disciplinary outputs.

From these experiences, it can be seen in interdisciplinary research, GIScientists must learn to maintain a balance, knowing when to compromise or not regarding their discipline. In Adaptable Suburbs, it would have perhaps been better to have had multiple or smaller, more achievable aims or to have proposed a compromise with project collaborators. In EHR and Challenging RISK, researchers were resourceful enough to determine how to still derive viable outputs, even though project goals had to be adjusted and there was diminished impact of interdisciplinary outputs.

4.3. Theme 3: go beyond your discipline

This theme is a key feature in interdisciplinary research. Whilst the GIScientists involved in the case studies were aware this, working on these projects gave the GIScientists a deeper understanding and appreciation of the necessity of the theme. As the GIScientists on the Adaptable Suburbs project aided the various disciplinary workstreams, it was necessary for them to quickly learn and apply methodologies and frameworks from other fields. Traditionally, GIScientists would consider the output of the map to be the end product of geospatial analytical work; however, through the approach the Architects on the project employed, their analysis began once they received the map and visually adjusted its outputs to highlight patterns in network flow and integration. Working with the Anthropologists required GIScientists to learn engagement methods and the nuances around participatory action research. As participants were intricately involved in the project, and bonds of trust were built with them, it was a requirement that decisions on the project that affected them were to be discussed with and involve them. GIScientists worked together with the Anthropologists to facilitate workshops and aided with processing qualitative outputs. As can be seen from these examples, the GIScientist had to adeptly learn to use and incorporate foreign disciplinary methodologies, which added an extra level of challenge for them.

While working with the EHR, the GIScientist learned much about the social structure of hospitals and how it influences data procurement and management. By working directly in a hospital setting where data were collected and entered into health records, the GIScientist had to learn why certain data were collected while others were not. This led the GIScientists to learn new skills such as how to conduct a usability evaluation. The GIScientist in this project had no prior experience with usability evaluation but it was clear that success or failure of this project hinged on usability, thus the GIScientist quickly learned and implemented a usability evaluation to ensure that data were collected at all. Others involved in the project did not learn about GIScience or usability more broadly.

The GIScientists on Challenging RISK learned much about the other disciplines and their methodologies. A list of key literature from each of the disciplines on the project was distributed and team members were required to read everything. Afterward, researchers met to discuss content and were encouraged to ask questions about anything they did not understand. For the GIScientists, this knowledge was necessary to assemble the GIS and maps that others required to complete their work. This information also influenced the direction of the participatory GIS led by the GIScientists during community workshops.

In each of these examples, the project started out with positive intentions for working together. By being open minded and intellectually curious, the GIScientists built a common ground with researchers from the other disciplines. External methodologies and collaborative skills that the GIScientists learnt are competencies they will keep and may be applied to future projects. Such insights may provide benefit with regard to employment and inclusion on future interdisciplinary projects.

4.4. Theme 4: benefits, but also limitations, to collaboration

GIScientists on Adaptable Suburbs were required to complete the digitization of historic and contemporary business data that were necessary for interdisciplinary outputs; however, a substantial workload was involved with completing the task. Regular group meetings were held between the GIScientists and the rest of the research team solely for understanding and correctly mapping historic data and the contemporary data collection was carried out by a temporary research assistant. Categorization of data by land-use types and determining which businesses belonged to which road segment when it was not clear, was difficult and required guidance and verification from the principal investigator. Though time-consuming, because the methodology was agreed amongst the team, this ensured a higher quality of output. Analyses using these data and associated results contributed to a subsequent book chapter highlighting high street economic diversity and change over time.

The two principal investigators in the EHR project have a history of sharing ideas and resources and have built a professionally collaborative relationship. As such, the research team for this project is largely amorphous, which positively contributes to its productivity, and the work is ongoing. The team was ultimately successful in producing an EHR that was used by surgeons in Cape Town, South Africa (Zargaran et al., 2014). Findings from researchers have been applied to a wide range of studies and are continually evolving with new findings. There are normal challenges with this research group in terms of identifying appropriate methods and techniques based on subsections of the project. It became important for the GIScientists to understand and address the social hierarchy in the hospital and account for that in the design of an EHR for spatial data collection to ensure that data collection needs were met.

It was difficult to find opportunities for the Challenging RISK research project to truly work in an interdisciplinary fashion. If working too closely, the flexible mixed methods approaches presented by the GIScientist's participatory research required of the GIScience project had the potential to disrupt the Psychologist's research goals in this study. The resulting solution to balance priorities among these interdisciplinary actors was to operate in parallel rather than collaboratively in the research site and not work with the same sample population. However, the Psychologist's survey was piloted with groups initially identified by the GIScientists to ensure it was robust and fit for purpose. Further contact details were also shared to assist the Psychologist with engaging with city officials and community champions. There were also publications on shared research outputs early in the project associated with literature reviews, initial data collection efforts and app prototyping with Engineers (Verrucci et al., 2016).

Good relationships on these projects helped researchers work together to identify mutually beneficial situations and facilitate communal outputs. Such collaboration, though, requires researchers to devote extra time to consider and review methodologies. Having supportive and understanding principal investigators who also have experience in interdisciplinary research can provide researchers valuable guidance. By carefully working through concerns and issues and being sensitive to all stakeholders' needs, GIScientists can ensure GIS analyses and products are relevant and impactful to the project.

5. Discussion

5.1. Modern GIS and science & technology studies

Reflecting on the case studies, each of them aimed to use modern GIS capabilities in interesting ways. Adaptable Suburbs wanted to employ GIS as a web platform for to collect Anthropological information, create a geospatial metadata storage solution and analyze geographic changes to roads and buildings across time periods. The EHR project hoped to create a sustainable geospatial data and metadata collection tool, to then visualize outputs that could positively impact operational procedures and understanding of the distribution of injuries. Challenging RISK, though unable to fully realize a bespoke mobile geospatial data collection platform, implemented an existing commercial one to gather data to offer insight into disaster preparedness, and act as a visual communication platform with community members. Given the ubiquity of web and mobile devices, it is not surprising that these projects wanted to use them as part of innovative scientific initiatives.

However, as geospatial technologies evolve, social and ethical implications of use and outputs should continually be evaluated to ensure fair use.

STS issues arose regarding application of GIS in each of these cases. In Adaptable Suburbs, the GIScientists needed to understand the sensitivity of the community information and how participants were equal partners on the project. By enforcing a certain viewpoint associated with the web GIS platform and its use, and not negotiating this with the participants and Anthropologists, the relationship with them was destabilized and this part of the project was not as successful as it could have been. For the EHR project, it was initially difficult for the GIScientist to communicate the importance of capturing associated geographic information, though they were able to make alternative arrangements for data collection and highlight to participants the social and organizational benefits of GIS. GIScientists on Challenging RISK involved participants from the beginning in the design of the custom GIS application and the switch to the commercial product. Democratization of the creation process and community members setting the boundaries of use successfully embedded Critical GIS principles in the project, and was key to communally agreed and beneficial outputs. Overall, GIScientists should be conscious that GIS can have positive and negative impacts on communities as well as the work of other researchers.

5.2. Interdisciplinary research and GIScience

Interdisciplinary research provides opportunities to better understand and address real world problems and to create sustainable solutions. These projects all aspired to achieve this by bringing a variety of researchers from different disciplines together and using GIS and GIScience concepts. Each of the case studies had varying levels of success in achieving their initial interdisciplinary aims. The level of interdisciplinary collaboration fluctuated over time on each project and researchers had to adjust. GIScientists planning on undertaking interdisciplinary work need to be aware of the challenges associated with these collaborations to develop effective mitigation strategies. They will need to keep an open mind, quickly learn the tools/methodologies from the disciplines of project partners and demonstrate how GIS can benefit the project.

GIS and GIScience have much to offer interdisciplinary research initiatives, but researchers will need to be careful to avoid potential pitfalls. As experienced in the case studies, some benefits of GIS were realized at certain points and it was able to deliver outputs that might not have been possible otherwise. However, in other situations, it either did not contribute anything novel or provide wider benefits. Sometimes this was due to not understanding the perspectives of participants and other researchers; at other points it was because GIScientists were not able to articulate and highlight the importance of their needs as well. The GIScientists did have the level of technical expertise required for these projects to create the necessary tools/outputs and upskill the other researchers as necessary. Without that expertise, it might not have been possible to deliver against the disciplinary and interdisciplinary goals.

5.3. Geographic information: tool, toolmaker, scientist

For these interdisciplinary projects, there was a communal desire for the incorporation of GIS as its benefits for geographic analyses were recognized across disciplines. However, it was up to the GIScientists on these projects to reflect on where they could add value and outline those benefits, while being aware of not injecting it into methodologies and areas of analyses where it was not needed. To accurately assess this, there were initial discussions on the level of complexity of GIS use when the project proposals were written – whether it was to use GIS as a Tool, needed a GIS Toolmaker, or required a GIScientist. This embodies some of the confusion around whether GIS is a tool or a science, but this postulation did not stop researchers on these projects from taking necessary action. Regardless, the use of GIS changed over time in each of the projects. Adaptable Suburbs largely needed a GIS Toolmaker to make the web GIS platform that was to be used to gather community information; later, when this was not used by project participants, the GIScientists instead focused on geospatial analyses and advised researchers in spatial classification efforts as part of the historic investigations. GIS was also employed as a tool to produce visuals for presentations and publications. In the EHR project, a GIS Toolmaker assisted in the design and construction of the data collection tool and developed the evaluation framework that was used throughout the project and beyond, while also using GIS as a tool for the outputs. The ethical implications of the data collected were of concern to all researchers; however, the spatial aspects (equal access to medical treatment, hot spots of particular injuries, etc. and what that might mean to communities) were of more importance to the GIScientist, who delved deeper into such topics as part of their personal research. Challenging RISK also required a GIS Toolmaker to construct the data collection tool; however, due to time constraints a commercial platform was used instead, which was only an application of GIS as a tool. GIScience concepts around ethical issues and concerns associated with the community were embedded in the project, so the GIScientist still had an important role to play.

To create the funding proposals for these projects, the use of GIS needed to initially be assessed and appropriately factored in for resourcing. Even within the use of GIS as a tool, solutions created by a GIS Toolmaker or analyses of a GIScientist, it must be noted that skill levels with GIS will vary. On Adaptable Suburbs, there were four GIScientists, the EHR project had two, and Challenging RISK also had two alongside a researcher who was skilled up to the equivalent level of a GIS technician (see Figure 1). Use of GIS on these projects fluctuated over time and as tasks changed the GIS skill level needed diminished; however, by having GIScientists, the projects were guaranteed to have the necessary GIS expertise. There were points, though, where GIScientists were underutilized on the projects for interdisciplinary outputs and so they focused on disciplinary ones. It is important for interdisciplinary projects to accurately assess this so they have the right people with the necessary skills, but recognize that greater expertise will generally cost more to resource, which must be taken into consideration when estimating funds in the initial project proposal.

6. Conclusion

As tools associated with geospatial technologies are advancing and becoming increasingly accessible, with ever more spatial data are being produced, there will consistently be growing opportunities for interdisciplinary research. Though enthusiastic about what GIS and GIScience offer such research, we must also recognize the social and ethical implications of GIS use and ensure a wide range of stakeholders are included in its design and implementation. Interdisciplinary research and use of GIS in it comes with unique social and technical challenges that must be acknowledged and addressed to realize associated benefits. GIS can be applied in interdisciplinary research by implementing GIS as a Tool, a GIS Toolmaker making bespoke tools or a GIScientist performing complex and advanced spatial analysis and navigating social, technical and ethical ambiguities. These roles have been defined using existing GIS job classes (Figure 1) and we must recognize varying skill levels within. Researchers embarking on interdisciplinary research projects may use these job classes to determine the skills they need for their project and resource it accordingly, while mindful of the goals they wish to achieve with GIS. As is the case with interdisciplinary research, tasks can change and GIS needs can fluctuate, so that may need to be factored in when considering project resourcing and funding.

Observations of the phenomena experienced in three case studies (Adaptable Suburbs, EHR, Challenging RISK) were presented, outlining the disciplinary and interdisciplinary goals of each of the actors on these projects. These were then explored based on common themes experienced by researchers, which were: 1) advocate for your discipline, 2) consequences for too much or too little focus on your discipline, 3) go beyond your discipline, and 4) benefits, but also limitations, to collaboration. Each of these were elaborated upon for the individual case studies, with technical and non-technical challenges shared as well as how the researchers successfully (and sometimes creatively) achieved valuable outcomes despite the obstacles. Many of these issues were overcome through a combination of established personal and disciplinary knowledge, as well as interdisciplinary skills obtained by the researchers over the lifetime of their respective projects. The researchers quickly learnt what is necessary about other disciplines involved on projects, and building an understanding of unfamiliar methodologies. They also became more sensitive to the social implications and nuances associated with the validation of other disciplines' analyses. They equally ensured that GIS and utilized aspects of GIScience are employed in an appropriate and meaningful way to both participants and fellow researchers. Finally, they appreciated that genuine interest and enthusiasm for interdisciplinary work, as well as the desire to collaborate with others, can help provide incentives to bring projects to completion. These can be considered requirements for GIScientists embarking on interdisciplinary research projects.

We hope that discussing these experiences will enable researchers to reflect, have productive discussions and develop strategies to improve future interdisciplinary research projects for GIS and GIScience. Ideas presented here can inform the selection process for the appropriate researcher with the necessary GIS skills for an interdisciplinary research project, as well as GIScientists considering a position within an interdisciplinary project.

Acknowledgments

The authors would like to first thank the participants in the studies that have been mentioned in this paper. We would also like to thank those who collaborated with us in the interdisciplinary research in the past and in the future. We have learned so much from each of you. Special thanks to Nadine Schuurman and Francis Harvey for offering feedback on early iterations of this manuscript, and to Nick Chrisman for his input on this final version. Finally, we would also like the thank the anonymous reviewers of each iteration of this manuscript

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

The research in this paper was supported by the Engineering and Physical Sciences Research Council (Grants EP/I025278/1, EP/I001212/1, and EP/K022377/1).

ORCID

B. A. Ricker http://orcid.org/0000-0001-5256-7824
P. R. Rickles http://orcid.org/0000-0002-8159-4319
G. A. Fagg http://orcid.org/0000-0002-5149-1132
M. E. Haklay http://orcid.org/0000-0001-6117-3026

References

Au, K. (1998). Social constructivism and the school literacy learning of students of diverse backgrounds. *Journal of Literacy Research*, *30*(2), 297–319. https://doi.org/10.1080/10862969809548000

Baerwald, T. (2010). Prospects for geography as an interdisciplinary discipline. *Annals of the Association of American Geographers*, *100*(3), 493–501. https://doi.org/10.1080/00045608.2010.485443

Barry, A., & Born, G. (Eds.). (2013). *Interdisciplinarity: Reconfigurations of the social and natural sciences*. Routledge. https://doi.org/10.4324/9780203584279

Becher, T., & Trowler, P. R. (2001). *Academic tribes and territories: Intellectual enquiry and the culture of disciplines*. McGraw-Hill Education.

Bhat, M. A., Shah, R. M., & Ahmad, B. (2011). Cloud computing: A solution to geographical information systems (GIS). *International Journal on Computer Science and Engineering*, *3*(2), 594–600. http://www.enggjournals.com/ijcse/doc/IJCSE11-03-02-006.pdf

Blaschke, T., & Merschdorf, H. (2014). Geographic information science as a multidisciplinary and multiparadigmatic field. *Cartography and Geographic Information Science*, *41*(3), 196–213. https://doi.org/10.1080/15230406.2014.905755

Bloor, D. (1976). *Knowledge and social imagery*. Routledge and Kegan Paul.

Boix Mansilla, V., & Dawes Duraisingh, E. (2007). Targeted assessment of students' interdisciplinary work: An empirically grounded framework proposed. *Journal of Higher Education*, *78*(2), 215–237. https://doi.org/10.1353/jhe.2007.0008

Bowlick, F. J., Goldberg, D. W., & Bednarz, S. W. (2017). Computer science and programming courses in geography departments in the United States. *Professional Geographer*, *69*(1), 138–150. https://doi.org/10.1080/00330124.2016.1184984

Bruce, A., Lyall, C., Tait, J., & Williams, R. (2004). Interdisciplinary integration in Europe: The case of the Fifth Framework programme. *Futures*, *36*(4), 457–470. https://doi.org/10.1016/j.futures.2003.10.003

Chen, X. M. (1998). Integrating GIS education with training: A project-oriented approach. *Journal of Geography*, *97*(6), 261–268. https://doi.org/10.1080/00221349808978843

Chrisman, N. (2005). Full circle: More than just social implications of GIS. *Cartographica: The International Journal for Geographic Information and Geovisualization*, *40*(4), 23–35. https://doi.org/10.3138/8u64-k7m1-5xw3-2677

Cinnamon, J., & Schuurman, N. (2013). Confronting the data-divide in a time of spatial turns and volunteered geographic information. *GeoJournal*, *64*(4), 657–674. https://doi.org/10.1007/s10708-012-9458-6

Clawson, D. L., & Johnson, M. L. (Eds.). (2004). *World regional geography: A development approach* (8th ed.). Pearson Prentice Hall.

Collins, H. M. (1981). Understanding science. *Fundamentals of Science*, *2*, 367–380. http://orca.cf.ac.uk/89940/

Connors, J., Lei, S., & Kelly, M. (2012). Citizen science in the age of neogeography: Utilizing volunteered geographic information for environmental monitoring. *Annals of the Association of American Geographers*, *102*(2), 1267–1289. https://doi.org/10.1080/00045608.2011.627058

Couclelis, H. (2012). 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), 2291–2300. https://doi.org/10.1080/13658816.2012.713959

Davé, A., Hopkins, M., Hutton, J., Krčál, A., Kolarz, P., Martin, B., Nielsen, K., Rafols, I., Rotolo, D., Simmonds, P., & Stirling, A. (2016). *Landscape review of interdisciplinary research in the UK*. University of Sussex. http://sro.sussex.ac.uk/id/eprint/65332/1/2016HEFCE_Landscape%20review%20of%20UK%20interdisciplinary%20research.pdf

Dibiase, D., Demers, M., Johnson, A., Kemp, K., Taylor Luck, A., Plewe, B., & Wentz, E. (2007). Introducing the first edition of geographic information science and technology body of knowledge. *Cartography and Geographic Information Science*, *32*(2), 113–120. https://doi.org/10.1559/152304007781002253

Dramowicz, K., Wightman, J. F., & Crant, J. S. (1993). Addressing GIS personnel requirements: A model for education and training. *Computers, Environment and Urban Systems*, *17*(1), 49–59. https://doi.org/10.1016/0198-9715(93)90006-q

Elmer-DeWitt, P. (2015, June 16). Why 3.5 times more apple users choose apple maps over google maps. *Fortune*. https://fortune.com/2015/06/16/apple-google-maps-ios/

Elwood, S. (2010). Geographic information science: Emerging research on the societal implications of the geospatial web. *Progress in Human Geography*, *34*(3), 349–357. https://doi.org/10.1177%2F0309132509340711

Elwood, S., Goodchild, M. F., & Sui, D. Z. (2012). Researching volunteered geographic information: Spatial data, geographic research, and new social practice. *Annals of the Association of American Geographers*, *102*(3), 571–590. https://doi.org/10.1080/00045608.2011.595657

Elwood, S., & Leszczynski, A. (2013). New spatial media, new knowledge politics. *Transactions of the Institute of British Geographers*, *38*(4), 544–559. https://doi.org/10.1111/j.1475-5661.2012.00543.x

Fenwick, T. J. (2010). (un)Doing standards in education with actor-network theory. *Journal of Education Policy*, *25*(2), 117. https://doi.org/10.1080/02680930903314277

Golding, C. (2009). *Integrating the disciplines: Successful interdisciplinary subjects. Melbourne: Centre for the study of higher education, University of Melbourne*. Centre for the Study of Higher Education. https://teachingcommons.lakeheadu.ca/

sites/default/files/inline-files/Integrating%20the%20Disciplines%20Successful%20Interdisicplinary%20subjects.pdf.

Goodchild, M. F. (2004). Communicating geographic information in a digital age. *Annals of the Association of American Geographers*, *90*(2), 344–355. https://doi.org/10.1111/0004-5608.00198

Goodchild, M. F. (2007a). Citizens as sensors: The world of volunteered geographic information. *GeoJournal*, *69*(4), 211–221. https://doi.org/10.1007/s10708-007-9111-y

Goodchild, M. F. (2007b). Citizens as voluntary sensors: Spatial data infrastructure in the world of web 2.0. *International Journal of Spatial Data Infrastructure Research*, *2*, 24–32. https://ijsdir.sadl.kuleuven.be/index.php/ijsdir/article/view/28

Goodchild, M. F. (2009). NeoGeography and the nature of geographic expertise. *Journal of Location Based Services*, *3*(2), 82–96. https://doi.org/10.1080/17489720902950374

Gouveia, C., & Fonseca, A. (2008). New approaches to environmental monitoring: The Use of ICT to explore volunteered geographic information. *GeoJournal*, *72*(3), 185–197. https://doi.org/10.1007/s10708-008-9183-3

Graham, M., & Zook, M. (2011). Visualizing global cyberscapes: Mapping user-generated placemarks. *Journal of Urban Technology*, *18*(1), 115–132. https://doi.org/10.1080/10630732.2011.578412

Haklay, M. (2017). Beyond quantification: A role for citizen science and community science in a smart city. In R. Kitchin, T. P. Lauriault, & G. McArdle (Eds.), *Data and the City* (pp. 213–224). Routledge. https://doi.org/10.4324_9781315407388-16

Harvey, F. (1997). From geographic holism to geographic information system. *Professional Geographer*, *49*(1), 77–85. https://doi.org/10.1111/0033-0124.00058

Harvey, F., & Chrisman, N. (2004). The imbrication of geography and technology: The social construction of geographic information systems. In S. D. Brunn, S. L. Cutter, & J. W. Harrington (Eds.), *Geography and Technology* (pp. 65–80). Springer. https://doi.org/10.1007/978-1-4020-2353-8_4

Harvey, F., & Chrisman, N. (1998). Boundary objects and the social construction of GIS technology. *Environment and Planning A*, *30*(9), 1683–1694. https://doi.org/10.1068/a301683

Holst, A. (2018, March 12). Smartphones industry: Statistics & facts. *Statista*. https://www.statista.com/topics/840/smartphones/

Huxhold, W. (Ed.). (2000). *Model job descriptions for GIS professionals*. Urban and Regional Information Systems Association.

Johannes, M. N., & Kasteren, V. (1996). Interdisciplinary teaching within engineering education. *European Journal of Engineering Education*, *21*(4), 387–392. https://doi.org/10.1080/03043799608923424

Johnson, A. B. (2006, September). Developing a GIS curriculum. *Esri Press*. https://www.esri.com/news/arcuser/0706/curricula.html

Johnson, J. (2010). What GIS technicians do: A synthesis of DACUM job analysis. *Journal of the Urban and Regional Information Systems Association*, *22*(2), 31–40. https://www.urisa.org/clientuploads/directory/Documents/Journal/Vol22No2.pdf

Kirby, R., Delmelle, E., & Eberth, J. (2017). Advances in spatial epidemiology and geographic information systems. *Annals of Epidemiology*, *27*(1), 1–9. https://doi.org/10.1016/j.annepidem.2016.12.001

Kitchin, R. (2014). *The data revolution: Big data, open data, data infrastructures and their consequences*. SAGE. https://doi.org/10.4135/9781473909472

Kuhn, W. (2012). Core concepts of spatial information for transdisciplinary research. *International Journal of Geographical Information Science*, *26*(12), 2267–2276. https://doi.org/10.1080/13658816.2012.722637

Lau, L., & Pasquini, M. (2008). "Jack of all trades"? The negotiation of interdisciplinarity within geography. *Geoforum*, *39*(2), 552–560. https://doi.org/10.1016/j.geoforum.2006.08.013

Lawrence, V. (2008, November 28). *The role of a national mapping agency in geoinformation management*. Ordnance Survey. http://www.fig.net/pub/fig2009/ppt/ps01/ps01_lawrence_ppt_3505.pdf

Longley, P. A., Goodchild, M. F., Maguire, D. J., & Rhind, D. W. (2010). *Geographic information systems and science* (3rd ed.). Wiley.

Lui, L., Li, W., Qiu, H., & Sun, C. (2012). Research and realization of GIS network education system. *IERI Procedia*, *2*, 276–281. https://doi.org/10.1016/j.ieri.2012.06.088

Mark, D. M. (2003). Geographic information science: Defining the field. In M. Duckham, M. Goodchild, & M. Worboys (Eds.), *Foundations of geographic information science* (pp. 1–18). Taylor & Francis. https://doi.org/10.1201/9780203009543.ch1

Milson, A. J., & Earle, B. D. (2008). Internet-Based GIS in an inductive learning environment: A case study of ninth-grade geography students. *Journal of Geography*, *106*(6), 227–237. https://doi.org/10.1080/00221340701851274

Mitchell, L., Frank, M. R., Harris, K. D., Dodds, P. S., & Danforth, C. M. (2013). The geography of happiness: Connecting twitter sentiment and expression, demographics, and objective characteristics of place. *PloS One*, *8*(5), e64417. https://doi.org/10.1371/journal.pone.0064417

National Academy of Sciences, National Academy of Engineering and Institute of Medicine. (2004). *Facilitating interdisciplinary research*. Academies Press. https://doi.org/10.17226/11153

National Science Foundation. (n.d.) *Introduction to interdisciplinary research*. National Science Foundation. https://www.nsf.gov/od/oia/additional_resources/interdisciplinary_research/

Nuckols, J. R., Ward, M. H., & Jarup, L. (2004). Using geographic information systems for exposure assessment in environmental epidemiology studies. *Environmental Health Perspectives*, *112*(9), 1007–1015. https://doi.org/10.1289/ehp.6738

O'Cathain, A., Murphy, E., & Nicholl, J. (2008). Multidisciplinary, interdisciplinary, or dysfunctional? Team working in mixed-methods research. *Qualitative Health Research*, *18*(11), 1574–1585. https://doi.org/10.1177/1049732308325535

Openshaw, S. (1993). Commentary: GIS 'crime' and GIS 'criminality'. *Environment and Planning A*, *25*(4), 451–458. https://doi.org/10.1068/a250451

Organisation for Economic Co-operation and Development/Organisation de Cooperation et de Development

Economiques (OECD). (n.d.) *Recognition of non-formal and informal learning - home*. Organisation for Economic Co-operation and Development/Organisation de Cooperation et de Development Economiques. http://www.oecd.org/education/skills-beyond-school/recognitionofnon-formalandinformallearning-home.htm

Paul, M. J., & Dredze, M. (2011, July 17-21). *You are what you tweet: Analyzing twitter for public health* [Paper presentation]. Fifth International AAAI Conference on Weblogs and Social Media, Barcelona, Spain. doi: https://doi.org/10.1.1.224.9974.

Pereira, J. M. C., & Itami, R. M. (1991). GIS-based habitat modeling using logistic multiple regression: A study of the Mt. Graham Red Squirrel. *Photogrammetric Engineering and Remote Sensing*, *57*(11), 1475–1486. https://www.asprs.org/wp-content/uploads/pers/1991journal/nov/1991_nov_1475-1486.pdf

Pickering, A. (1995). *The mangle of practice*. University of Chicago Press.

Poore, B. S., & Chrisman, N. R. (2006). Order from noise: Toward a social theory of geographic information. *Annals of the Association of American Geographers*, *96*(3), 508–523. https://doi.org/10.1111/j.1467-8306.2006.00703.x

Rana, S., & Joliveau, T. (2009). NeoGeography: An extension of mainstream geography for everyone made by everyone? *Journal of Location Based Services*, *3*(2), 75–81. https://doi.org/10.1080/17489720903146824

Reitsma, F. (2013). Revisiting the 'is GIScience a science?' debate (or quite possibly scientific gerrymandering). *International Journal of Geographical Information Science*, *27*(2), 211–221. https://doi.org/10.1080/13658816.2012.674529

Ricker, B. (2017). GIS. In R. Kitchin, R. Lauriault, & M. W. Wilson (Eds.), *Understanding spatial media* (pp. 12–34). Springer. https://doi.org/10.4135/9781526425850.n2

Rickles, P., & Ellul, C. (2014). *Identifying important geographic information system concepts in interdisciplinary research: An analysis of google scholar* [Paper presentation]. GIS Research UK, Glasgow, Scotland.

Rickles, P., & Ellul, C. (2015). A preliminary investigation into the challenges of learning GIS in interdisciplinary research. *Journal of Geography in Higher Education*, *39*(2), 226–236. https://doi.org/10.1080/03098265.2014.956297

Roth, R. E. (2009). A qualitative approach to understanding the role of geographic information uncertainty during decision making. *Cartography and Geographic Information Science*, *36*(4), 315–330. https://doi.org/10.1559/152304009789786326

Rouse, L. J., Bergeron, S. J., & Harris, T. M. (2007). Participating in the geospatial web: Collaborative mapping, social networking and participatory GIS. In A. Scharl & K. Tochterman (Eds.), *The geospatial web: How geobrowsers, social software and the web 2.0 are shaping the network society* (pp. 3–14). Springer. https://doi.org/10.1007/978-1-84628-827-2_14

Schulz, B. (2008). The importance of soft skills: Education beyond academic knowledge. *Journal of Language and Communication*, *2*(1), 146–154. http://ir.nust.na/handle/10628/39

Schuurman, N., Cinnamon, J., Matzopoulos, R., Fawcett, V., Nicol, A., & Hameed, S. M. (2011). Collecting injury surveillance data in low-and middle-income countries: The Cape Town Trauma registry pilot. *Global Public Health*, *6*(8), 875–889. https://doi.org/10.1080/17441692.2010.516268

See, L., Mooney, P., Foody, G., Bastin, L., Comber, A., Estima, J., Fritz, S., Kerle, N., Jiang, B., Laasko, M., Liu, H., Olteanu-Raimond, A., Rutzinger, M., Painho, M., Pődör, A., Olteanu-Raimond, A.-M., & Rutzinger, M. (2016). Crowdsourcing, citizen science or volunteered geographic information? The current state of crowdsourced geographic information. *ISPRS International Journal of Geo-Information*, *5*(5), 55. https://doi.org/10.3390/ijgi5050055

Sheppard, E. (2005). Knowledge production through critical GIS: Genealogy and prospects. *Cartographica: The International Journal for Geographic Information and Geovisualization*, *40*(4), 5–21. https://doi.org/10.3138/gh27-1847-qp71-7tp7

Sieber, R. E., Robinson, P. J., Johnson, P. A., & Corbett, J. M. (2016). Doing public participation on the geospatial web. *Annals of the American Association of Geographers*, *106*(5), 1030–1046. https://doi.org/10.1080/24694452.2016.1191325

Soja, E. (2009). Taking Space Personally. In B. Warf & S. Arias (Eds.), *The spatial turn: Interdisciplinary perspectives* (pp. 11–35). Routledge. https://doi.org/10.4324/9780203891308-8

Stember, M. (1991). Advancing the social sciences through the interdisciplinary enterprise. *Social Science Journal*, *28*(1), 1–14. https://doi.org/10.1016/0362-3319(91)90040-b

Sui, D. (2008a). Is neogeography hype or hope? *GeoWorld*, *21*(3), 16–17.

Sui, D. (2008b). The wikification of GIS and its consequences: Or Angelina Jolie's new tattoo and the future of GIS. *Computers, Environment and Urban Systems*, *32*(1), 1–5. https://doi.org/10.1016/j.compenvurbsys.2007.12.001

Sui, D., & Goodchild, M. F. (2001). GIS as Media? *International Journal of Geographical Information Science*, *15*(5), 387–390. https://doi.org/10.1080/13658810110038924

Sui, D., & Goodchild, M. F. (2011). The convergence of GIS and social media: challenges for GIScience. *International Journal of Geographical Information Science*, *25*(11), 1737–1748. https://doi.org/10.1080/13658816.2011.604636

The role of geospatial information in the sustainable development goals. (2015). United Nations Secretariat – Global Geospatial Information Management (UN-GGIM). http://ggim.un.org/knowledgebase/Attachment158.aspx?AttachmentType=1

Turner, A. (2006). *Introduction to neogeography*. O'Reilly Media Inc.

Van Noorden, R. (2015). Interdisciplinary research by the numbers. *Nature News*, *525*(7569), 306–307. https://doi.org/10.1038/525306a

Verrucci, E., Perez-Fuentes, G., Rossetto, T., Bisby, L., Haklay, M., Rush, D., Rickles, P., Fagg, G., & Joffe, H. (2016). Digital engagement methods for earthquake and fire preparedness: A review. *Natural Hazards*, *83*(3), 1583–1604. https://doi.org/10.1007/s11069-016-2378-x

Warf, B., & Arias, S. (2009a). Introduction: The reinsertion of space into the social sciences and humanities. In B. Warf & S. Arias (Eds.), *The spatial turn: Interdisciplinary perspectives* (pp. 1–10). Routledge. https://doi.org/10.4324/9780203891308-7

Warf, B., & Arias, S. (2009b). *The spatial turn: Interdisciplinary perspectives*. Routledge. https://doi.org/10.4324/9780203891308

Wiersma, Y. (2010). Birding 2.0: Citizen science and effective monitoring in the web 2.0 World. *Avian Conservation and*

Ecology, *5*(2), 13–21. https://doi.org/10.5751/ace-00427-050213

Wright, D. J., Goodchild, M. F., & Proctor, J. D. (1997). GIS: Tool or science? Demystifying the persistent ambiguity of GIS as 'Tool' versus 'Science'. *Annals of the Association of American Geographers*, *87*(2), 346–362. https://doi.org/10.1111/0004-5608.872057

Zargaran, E., Schuurman, N., Nicol, A. J., Matzopoulos, R., Cinnamon, J., Taulu, T., Ricker, B., Garbutt Brown, D. R., Navsaria, P., & Morad Hameed, S. (2014). The electronic Trauma health record: Design and usability of a novel tablet-based tool for trauma care and injury surveillance in low resource settings. *Journal of the American College of Surgeons*, *218*(1), 41–50. https://doi.org/10.1016/j.jamcollsurg.2013.10.001