Frontiers of GIScience: Evolution, State-of-Art, and Future Pathways

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1.0 Introduction

Geographic Information Science (GIScience) is the science that underlies Geographic Information Systems (GIS) technology. Roger Tomlinson introduced GIS in his report on computer mapping and analysis to the National Land Inventory in the Canada Department of Agriculture (Tomlinson, 1962). Yet, when GIS is broadly defined as a system that deals with geographic information, it can be traced far back into the time when humans started recording and sharing knowledge about the environment. Before computer-based GIS technology, oral traditions and maps were primary means to communicate geographic information. Nowadays, GIS technologies are diverse and thriving in mapping, spatial analysis and modeling, location-based services, cyber geographical applications, and spatial crowd sourcing. GIS technologies now important research tools for research and operations in environmental sciences, biological and agricultural sciences, public health, urban planning, and economic, political, and social studies. GIScience serves the conceptual, theoretical, and computational foundations for these technologies.

Dating to ~6600 BC, the mural found at the Neolithic site of Catalhöyük, is considered the world's oldest map (Schmitt et al., 2014). The early adoption of maps is of no surprise. Maps are intuitive and effective ways to give directions, express spatial arrangements of features, and plan spatial activities. Humans made maps long before they invented writing. Likewise, Tomlinson's GIS was motivated by the use of computers to automate map analysis and production. To date, map libraries continue the important role of curating and providing access to atlases, aerial photographs and spatial data in digital forms, while massive and diverse geographic information is also widely available from government agencies, businesses, organizations, and communities.

While mapping is essential, a GIS also consists of tools to process geospatial data, manage geospatial databases, integrate data through geo-referencing and compatible attribute definitions, analyze embedded spatial patterns, model geographic phenomena and processes, and render data and findings in multiple ways. The technology was initially developed out of application needs, and its conceptual and computational frameworks were fragmented across solutions. GIScience research contributes to developing fundamental frameworks for GIS technologies and takes the technological challenges to improve our understanding of geographic information, processes for geographic knowledge building and communication, and spatial decision support.

This chapter aims to highlight the past, present, and future of GIScience research. As a field of interdisciplinary and multidisciplinary research, GIScience enjoys outstanding advances in both breadth and depth as evidenced by the multitude of names associated with the discipline, such as Geospatial Science, Spatial Science, Spatial Information Science, Geoinformatics, and Geomatics (Table 1). Consequently, it is challenging to capture the full scope of research development in the field. What follows reflects the author’s perspectives on the evolution, state of the art, and future pathways of GIScience. Since the chapter is focused on GIScience, the discussions here emphasize the key intellectual development of spatial concepts, theories, and computational approaches. GIS applications are not GIScience research and, therefore, are beyond the scope of this chapter. The next section elaborates on the evolution of GIS technologies to GIScience. From the early emphases on the transitions from technological advances in mapping, spatial database building, and inventory and planning applications to scientific inquiries into the nature of geographic information, spatial computing, and geographical understanding. Section 3 highlights the active GIScience research directions in cognition, representation, integration, and computation. The chapter concludes with promising pathways for future GIScience development.

Insert Table 1 here

2.0 Evolution

Computer-based GIS technology revolutionized the processes of recording and disseminating geographic information and invoked new possibilities to represent, analyze and compute geography. Since its conception, the term “GIS” was often referenced exclusively to computer-based GIS. Coppock and Rhind (1991) characterized the early development of computerized GIS into four general phases from 1960 to 1990:

(1) **A phase of pioneers** from the early 1960s to 1975. Key leaders included Howard Fisher of the Harvard Laboratory for Computer Graphics, Roger Tomlinson of the Canadian Geographic Information System, and David Bickmore at the Experimental Cartographical Unit in the United Kingdom.

(2) **A phase of national drivers** from 1973 to early 1980s. Key agencies included Canada’s Department of Agriculture, the United States Bureau of the Census, and the Ordnance Survey in Great Britain. In the United States, GIS technology attracted great interest from many

federal agencies such as the Department of Defense, Central Intelligence Agency, US Forest Service, Fish and Wildlife Service, and Department of Housing and Urban Development, as well as state and local governments including California, Maryland, Minnesota, New York, and others.

(3) **A phase of commercial dominance** from early to late 1980s, most noticeably the Environmental Systems and Research Institute (ESRI, now Esri) and Integraph. The companies not only developed GIS software packages but also designed and implemented GIS projects for government agencies. These GIS packages were adopted in college courses, and to date they remain the primary tools for learning GIS and doing GIS projects. In 1988, the United States National Science Foundation (NSF) awarded a grant to establish the National Center for Geographic Information and Analysis (NCGIA) with the University of California at Santa Barbara, State University of New York at Buffalo, and University of Maine. The NSF grant provided $10M dollars for 8 years of NCGIA leadership that transformed GIS to GIScience and resulted in lasting impacts in education and research in the US and around the world.

(4) **A phase of user dominance** since early 1990s with the rise of desktop GIS that emphasized ease of use and promoted wide adoption of GIS technology beyond research universities, large government organizations and big companies. In 1994, US Executive Order 12906 established the Federal Geographic Data Committee (FGDC) as the executive branch leadership to develop the National Spatial Data Infrastructure (NSDI) marked the first multi-agency nation-wide efforts to coordinate GIS data management and access. The expanded availability of free GIS data stimulated many geospatial research and business opportunities and popularized GIS technology in a wide range of domain applications.

In a short period of 30 years (1960s to 1990s), GIS started with a few visionaries who sought ways to use computers for mapping and analyzing geographic data and then grew to a generation of researchers and professionals that brought GIS into mainstream college curricula, government functions, and business operations. With this growth, research efforts went beyond mapping and spatial data handling. Researchers ventured into the unique complexity of geographic information and ensuing challenges in acquiring and using spatial data to understand geographic processes and make spatial predictions. *The International Journal of Geographical Information Systems* (*IJGIS*) was launched in 1987 and was recognized as the primary academic journal in the field (Caron et al., 2008). Goodchild published a landmark paper in *IJGIS*, entitled Geographic Information Science (Goodchild, 1992). The paper highlighted scientific problems unique to geographical data and established the topical content for GIScience.

Since then, many organizations and journals adopted the term GIScience over GIS. Efforts of the academic community, with most participants from Geography, established the University Consortium for Geographic Information Science (UCGIS) in 1994 and, through community efforts, defined GIScience as "*the development and use of theories, methods, technology, and data for understanding geographic processes, relationships, and patterns. The transformation of geographic data into useful information is central to geographic information science*"(UCGIS, 2002, Mark, 2003). It is important to note that GIScience research is not about using GIS technologies to solve scientific problems. This is similar to statistics and mathematics; applications of statistical or mathematical methods to solve a biological problem contribute to biological science, not the sciences of statistics or mathematics.

The early development of GIScience can be attributed to the NCGIA's leadership in a series of initiatives as well as the UCGIS community efforts to identify and articulate research challenges. In 1997, the *International Journal of Geographical Information Systems* was renamed *International Journal of Geographical Information Science* marking its second decade of publication (Fisher, 2006). However, the tendency to use GIScience as a synonym for GIS was quite common in early 2000 (Mark, 2003) and remains rather persistent today. Many programs offer GIScience courses with the same instructional materials for GIS, and many do not differentiate GIScience research from research using GIS. Nevertheless, leading journals (such as *IJGIS* and *Geoinformatics*) and conferences in GIScience (such as GIScience and ACM-SIGSPATIAL) emphases papers with contributions to conceptual, theoretical, and computational innovations.

Foundational work in cartography, spatial statistics, and spatial modeling has significantly contributed to the development of GIS, and these continue to be important subjects in GIScience research today. Computer cartography made notable progress in line generalization (Douglas and Peucker, 1973), map generalization (Buttenfield and McMaster, 1991), cartographic label placement (Marks and Shieber, 1991), and interactive digital atlases production (MacEachren, 1998). Landmark spatial studies led to new methods that account for local variations and local processes, such as Map Algebra (Tomlin, 1994), Local Indicator of Spatial Autocorrelation, a.k.a. LISA (Anselin, 1995), Geographically Weighted Regression, a.k.a. GWR (Brunsdon et al., 1998), and Geo-Algebra (Takeyama and Couclelis, 1997). Furthermore, spatial modeling advanced new approaches to simulate hydrological processes (Olivera and Maidment, 1999) and urban systems (Couclelis, 1997, Batty, 2007) by leveraging dynamic methods from other fields, such as distributed modeling, Cellular Automata (CA), and Agent Based Modeling (ABM).

Moreover, arguments were made that foundations of GIScience should tie closely to Information Science (Mark, 2003). Information Science studies the means and processes of information transmission among humans and/or computers. Syntactic form, semantic content, and contextual relevance are key elements in determining the value and optimal means of information flows from transmitters to receivers (Worboys, 2003). However, any judgment about value and optimality of the key elements must rely on a common understanding of the domain between transmitters and receivers. Geographic ontologies became an important subject in GIScience research (Agarwal, 2005), and research on spatial ontologies and representation along with other issues related to the nature of geographic information, was prominent in NCGIA research initiatives and UCGIS research challenges. Fundamental GIScience research has been promoted through the Conference on Spatial Information Theory (COSIT) starting in 1993 and International Conference on GIScience (GIScience) which began in 2000. Since, the two conferences have been held in alternate years and locations between Europe and North America. In addition, the Auto-Carto International Symposium on Automatic Cartography and International Symposium on Spatial Data Handling both have a long history as primary academic venues in GIScience. Computer Scientists interested in spatial database and information started the annual Association for Computing Machinery (ACM) Workshop on Advances in Geographic Information Systems in 1993. They successfully expanded the annual workshop to annual ACM-GIS International Symposium in 1998 and furthermore established the ACM Special Interest

Group on Spatial Information (SIGSPATIAL) as the catalyst for research on spatially-related information among computer scientists (Samet et al., 2008).

These pioneer efforts established a strong foundation for GIScience. Research has migrated from GIS enabling computerization of geographic data processing and mapping to GIScience inquiries into the essence of geographic information and epistemology. Goodchild (2014) highlighted research and institutional accomplishments in the 20 years of progress since the introduction of GIScience in 1994. On measurements, research foci shifted from spatial errors in the 1980s to spatial uncertainty in the 1990s. On representation, research advanced from vector/raster in the 1980s and objects/fields in the 1990s, to complex object-fields and field-objects in 2000s. GIScience research on analysis progressed from spatial autocorrelation in the 1970s to spatial heterogeneity in the 1990s. These efforts also built a strong foundation that support GIScience research and development into the mainstream of information technology. The GIScience evolution is summarized in Figure 1.

Insert Figure 1 here.

Over the years, GIScience research frontiers were articulated through 21 NCGIA research initiatives UCGIS research priorities and Computing Community Consortium Spatial Computing Visioning. Goodchild (2014) listed some of the topics that resulted from discussions in GIScience communities in several venues and summarized in a conceptual framework for GIScience that connects the dimensions of human, society, and computer. Expanded upon his conceptual framework, Figure 2 incorporates major developments in cyberinfrastructure and computing that have transformed the interplays among the human, society, and computers as well as how we perceive and understand human, physical, biological, and many other dimensions of reality. There is no shortage of research challenges in GIScience. This becomes evident with a quick search on Google Scholar which results in more than 5000 publications on the subject. Some fundamental topics remain outstanding and are likely to persist at the core of GIScience research, such as geographic ontologies, space-time representation, spatial algorithms, spatial cognition, geovisualization, and spatial decision support.

Insert Figure 2 here.

3.0 State-of-Art

GIScience continues to evolve with an increasing attention to what is local rather than global, individual rather than aggregated, collaborative rather than authoritative, culturally aware rather universal, open rather than exclusive, and mobile rather than desktop. Moreover, models and methods are being developed to represent and visualize multidimensional and multimedia data. Leveraged by the internet, new GIS platforms are being realized on the World Wide Web, with Cyber Infrastructure, and in the Cloud. All these developments have profound influences on what is summarized here as 3 A’s: *Abstraction*, *Algorithms*, and *Assimilation* throughout GIScience epistemology.

1.1 Abstraction

Abstraction takes place at multiple levels in GIScience research. It is concerned with how we conceptualize geographic worlds and spatial problems and subsequently how we represent, compute, and communicate all the relevant concepts and findings. As spatial data are from different sources, integration can be challenging at each level of abstraction. Perhaps, the most popular abstraction used in GIScience is the so-called data layers (Figure 3). While the data-layer abstraction is intuitive, GIScience research examines issues in cognition, ontology, and statistics (e.g. sampling) for better abstraction of reality.

Insert Figure 3 here.

Across all the levels of abstraction, cognitive research helps understand how people learn and organize geographic knowledge. Such cognitive understanding can improve GIS usability and communication. Montello (2009) summarized five main areas of cognitive research in GIScience since 1992: human factors of GIS, geovisualization (including spatialization), navigation systems, cognitive geo-ontologies, spatial thinking and memory, and cognitive aspects of geographic education. Much of the cognitive research confirms the complexity of geographic information and knowledge due to indeterminacy, vagueness, and the interdependency of individuals and geographic context. As a result, geographic categorization and reasoning may vary from person to person or place to place. For example, cognitive geo-ontologies recognize that people may see things differently, and their conceptualizations may vary due to environmental, cultural or linguistic differences (Mark et al., 2011, Wellen and Sieber, 2013, Turk and Stea, 2014). Such differences have profound implications for information sharing and integration, spatial data infrastructure building, spatial decision support, and many other issues that deal with the usefulness of GIS technologies and intrinsic technological biases.

Information sharing and integration was the initial motivator of ontological research through the rise of the Semantic Web that extends the World Wide Web for people to share and reuse data beyond application boundaries. Ontological approaches are now commonly used to define specifications of geographic abstractions in a problem domain (Jung et al., 2013, Ujang and Rahman, 2013), achieve semantic consistency for data integration and complex query support (Wiegand, 2012), and assure interoperability across systems and over web services (Shi and Nellis, 2013). Different frameworks have been proposed for geo-ontologies. Frank (2001) argued for a tiered ontology to assure consistency constraints based on how different kinds of things are conceptualized and from where they are abstracted. Tier 0 ontologies are for *human-independent reality* where natural laws prevails regardless of human observers. Tier 1 ontologies are for *observations of physical world* with measurements and statistics. Tier 2 ontologies are for *objects with properties* that can be used to identify individuals and determine categorical memberships with necessary and sufficient properties. Tier 3 ontologies are for *social reality* that is subject to social, cultural, and linguistic contexts. Finally, Tier 4 ontologies are for *subjective knowledge,* which may be incomplete or partial, used by individuals or institutions for reasoning or decision making. Couclelis (2010) articulated the need for geographic information constructs as the core of ontologies in GIScience. Her framework centers on an ontological hierarchy to connect intentionality and relevant information. There are seven levels of semantic resolution in the hierarchy. In the order of low to high levels, the semantic levels of resolution include *existence*, *observables*, *similarities*, *simple objects*, *composite objects*, *function*, and *purpose*. She introduced the idea of *semantic contraction* to generalize semantic richness from higher, more complex levels to a lower level of simpler semantics, and *object of discourse* to represent entities as composites of geographic information constructs at the higher levels of the hierarchy. This ontological research expanded our understanding of semantic granularity (Fonseca et al., 2002) and spatial tasks (Wiegand and García, 2007) and laid the foundation for building theories of geographic information.

In addition to ontologies, abstraction also accounts for means by which geographic information can be effectively acquired, analyzed, and communicated. Traditionally, geography is abstracted in forms of data from field surveys, maps, imagery, tables, graphs, and text. Advances have opened new means to acquire geographic information with new kinds of geographic abstraction. For example, data from dynamic geosensor networks (Llaves and Kuhn, 2014), tweets (Tsou et al., 2013), geotagged photos (Samet et al., 2013), and information from various social media (Croitoru et al., 2013, Jiang and Miao, 2014) offer real-time or near real-time environmental and social abstractions which enable detection of events and activities as they unfold. As the geographic world captured by these data is transitory and ephemeral, so is the ensuing geographic abstraction. Volunteered geographic information (VGI), crowdsourced geographic information (Goodchild, 2007, Goodchild and Glennon, 2010), and ambient geospatial information (Stefanidis et al., 2013) commonly condense information entries to point locations. Consequently, geographic abstraction is generally reduced to individuals and collections of points. Spatial synthesis would be more appropriate than analysis to decipher these data.

Besides geosensor and social media data, multimedia data incorporate video, audio, virtual reality, and augmented reality to represent geography (Camara and Raper, 1999). Videos may be interviews, documentary films, or animation of temporal information. Audios may be oral stories, narration by a native speaker, testimonies, songs, or animal sounds. Both video and audio enrich abstractions of geographic reality by enriching the context of spatial abstraction. Virtual reality and augmented reality, usually with 3D visualization, supplement spatial abstraction with videos, audios, photographs, digital documents, and labels in a dynamic context-aware immersive environment. Granularity of geographic abstraction becomes finer or coarser depending on the user's location and view. Virtual geographic environment (Lin et al., 2013) leverages virtual reality and multidimensional GIS to provide a digital platform for geographic experiments through collaborative visualization and simulation. Collaboration requires shared geographic abstraction of both declarative knowledge and procedural knowledge as the basis for communication and integration, which in turn rests on cognitive and ontological compatibility.

2.1 Algorithms

Algorithms are step-by-step procedures for calculations. Here, algorithms are broadly defined as approaches to data processing, analysis, modeling, and simulation. As geographic abstraction shifts emphases to semantics, the development of spatial algorithms also attempts to reveal local meanings and individual behaviors in space and time.

The rise of Critical GIS (O Sullivan, 2006, Schuurman, 2006) reflects the needs to engage social critiques in GIS-based geographic knowledge production in terms of basic concepts, representation, participation, and social implications. Volunteered geographic information (VGI) and web map services partially address the needs by empowering ordinary citizens to create geographic data and participate in geographic knowledge production. Many critical GIS researchers also echo the criticisms of positivist biases in GIS and advocate for qualitative GIS (Cope and Elwood, 2009) to address the needs to incorporate contextual details and interpretations of the described situation and processes. Broadened GIS methodology and the programming environmental allow qualitative methods that are commonly used by sociologists and humanities scholars, like coding, triangulating source materials, and content analysis in recursive and iterative forms to produce knowledge, such as Geo-Narrative (Kwan and Ding, 2008).

VGI is only one data source available from the Web. There are many crowdsourced systems (Yuen et al., 2011). For geospatial data, crowdsourced systems usually provide web map services or web feature services that support map mash-ups by which geospatial data from remote servers can be visually overlapped in a browser on a client site. As discussed in the abstraction section, the Semantic Web transforms web content to data as Web 2.0. Various social media facilitate crowdsourcing and provide ambient geographic information that can be exploited to recognize social pulses (Croitoru et al., 2013) or validate environmental conditions (See et al., 2013). Crowdsourced data are either directly requested by a project web service such as “Did you feel it?" web portal by the United States Geological Surveys (USGS) Earthquake Hazards Program[1] or harvested from social media feeds via application programming interfaces (API), such as OpenStreetMap API[2]. Heipke (2010) provided a good introduction on crowdsourcing geospatial data with highlights of successful projects, the basic technologies and comments on data quality.

Since VGI and crowdsourced data lack statistical sampling schemes and are collected from various sites, researchers need to develop customized algorithms for data preprocessing, mapping and analysis. Of great challenge is the fact that these data violate most, if not all, sampling assumptions based on which conventional statistical methods are founded. Location information associated with VGI, crowdsourced data, and data from web crawling may be explicitly tagged through GPS readings as latitude, longitude or other x, y coordinate pairs. Alternatively, location may be implicitly noted in forms of place names or addresses. Addresses can be matched through geocoding against street network databases. For place names, toponym resolution and gazetteer matching will be necessary for georeferencing (Adelfio and Samet, 2013). More generally, conceptual and computational frameworks are being developed to transform text to a rich geospatial data source (Vasardani et al., 2013, Yuan et al., 2014). While several studies showed that VGI and crowdsourced data are timely and at times more representative of geographic reality than authoritative data (Goodchild and Glennon, 2010), most VGI and geospatial crowdsourced projects remain primitive and do not go beyond visualization, animation, and frequency graphing (Batty et al., 2010). Because crowdsourced data collection does not follow any statistical sampling methods, they cannot be applied to established statistical

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[1] http://earthquake.usgs.gov/earthquakes/dyfi

[2] (http://wiki.openstreetmap.org/wiki/API_v0.6

models. Sentiment analysis of postings and messages is often based on keywords without reference to the content. A detailed view of crowdsourcing can be found in Chapter 26 of this Volume. Chapter 26 also provides many examples of crowdsourcing in spatial sciences.

Besides VGI and crowdsourced data, GIScience researchers are active in cyber infrastructure research and cloud computing. CyberGIS integrates GIS and spatial analysis and modeling into cyber infrastructure that provides high performance (terra grid) computing and large-scale data repositories (Wang et al., 2013). It transforms GIS from an isolated platform to a cyber-network of supercomputers, virtual organizations, and massive shared data resources. The fundamental differences in computing platforms require new algorithms for data processing, management, analysis, and modeling, and much has been implemented as middleware. While also taking the advantage of internet information technologies, cloud computing leverages four types of services: Infrastructure as a Service (IaaS), Platform as a Service (PaaS), Software as a Service (SaaS), and Data as a Service (DaaS), with open source resources Hadoop and MapReduce to offer elastic, distributed, and on demand computing facilities.

The ideas of spatial cloud computing encompass not only utilization of existing cloud services for intensive spatial computing but also the development of data and tool services for geospatial applications that are made accessible over the web (Yang et al., 2011). Cloud computing provides elastic, advanced resources for experimenting with ideas, application development, and app distribution. Location-aware or spatially enabled apps are widely available to map property values, routes, crime incidents, restaurants, and gas stations, for example. Cloud computing opens GIS workflows to tightly connect to resources on the web and transforms GIS into a service that frees users from desktop computers to anywhere and any platform with internet access. CloudGIS emerges as a promising platform for large-scale geospatial computing and opens many opportunities for mobile GIS, geosensors, and Spatial Big Data (Bhat et al., 2011, Shekhar et al., 2012, Fan et al., 2013).

Even before the introduction of Big Data, many spatial data are big and grow exponentially, especially imagery data and sensor data. The popularity of location-aware devices and geosensors have motivated algorithm development for trajectory analysis, geometrically (Li et al., 2011) or semantically (Yan et al., 2013) among other methods for movement modeling (Long and Nelson, 2012). Intensive observation updates of location-aware and sensor data further challenge hardware and software capacity. CudaGIS is an example of GIS design with GPUs to provide parallel data processing capabilities (Zhang and You, 2012). GPU algorithms are being developed to enable rapid urban simulation (Ma et al., 2008), Lidar data processing (Sugumaran et al., 2011), viewshed analysis and other data intensive computation (Steinbach and Hemmerling, 2012). Some of the parallel and GPU algorithms have been implemented in open source GRASS GIS for fast spatial computing and rendering (Osterman, 2012). With on-demand IaaS, GPU-based cloud computing has shown to be effective for intelligent transportation management (Wang and Shen, 2011). A detailed view of cloud computing can be found in Chapter 27 of this Volume. Chapter 27 also several examples of where and how cloud computing is used in spatial science.

3.1 Assimilation

Assimilation is defined in the Oxford English Dictionary as the action of becoming conformed to or conformity with. In this paper, assimilation is broadened to processes that bring individual's contributions to a commons for a greater good or to reveal a bigger picture. With the definition, assimilation efforts in GIScience have flourished through Open Source GIS, Social Coding, Open GIS, and Spatial Turns.

Open source GIS, like GRASS, Quantum GIS, and PostGIS, were developed by individuals through community efforts (Neteler and Mitasova, 2008) and have gained significant momentum since 2005. To date, there are more than 350 free and open source GIS software packages available[3]. Along with the free software are free data and documents to serve as a foundation for building a learning society in which source code, algorithms, and models can be tested and continuously improved upon. Steiniger and Bocher (2009) reviewed 10 free and open source GIS software packages and argued for the use of open source practices and software in research for transparency, testability, and adaptability to other projects. Many diverse open source GIS communities thrived in 2012 (Steiniger and Hunter, 2013). Assimilation of individual's contributions for tool development and code improvement in an open source environment collectively results in richer and better GIS resources for all. Social coding follows a similar idea of collaboration, but instead of working towards a package, social coding can be any project or program codes initiated by individuals rather than a community. Perhaps, the most popular social coding site is Github[4] where people can freely copy and modify codes to assimilate into other

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[3] http://freegis.org

[4] http://github.com

projects. There are many geospatial projects on Github, such as CartoDB, GeoNode, Spatial4J, OSGeo, and geopython. It is noteworthy that Esri is also active at Github with a suite of open source projects.

Another large-scale collaborative assimilation is the R project, an open source environment for statistical computing and graphics built upon the R language developed by Ihaka and Gentleman (1996). R users can study the source code to understand the underlying statistical procedures and assimilate their new modules with existing R methods, which facilitates advances in methodological research and opportunities to submit proposed models from publications for testing and reuse. Over the last 15 years, R has gained strong volunteer support in building various extensions, including packages for spatial statistics, for example, SpatStat (Baddeley and Turner, 2005), GeoXp (Laurent et al., 2009), and spacetime (Pebesma, 2012). The call for integration of GIS and spatial data analysis (Goodchild et al., 1992) was originally intended to add more spatial analysis capabilities to a GIS. Instead, much success has been realized by assimilating spatial data and methods into R statistics[5]. Currently, R consists of a large suite of spatial modules covering raster analysis, interpolation and geostatistics, spatiotemporal simulation models, spatial autocorrelation, spatial econometrics, spatial structure models, spatial Bayesian models, spatiotemporal cluster analysis, and various mapping and graphing tools (Bivand et al., 2013). In addition, efforts are being made to apply R directly to GRASS GIS database files (Bivand, 2000) or port R scripts to Quantum GIS (Solymosi et al., 2010). Similarly, spatial analysis functions are being assimilated into the Python programming

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[5] One may use R as a GIS (http://pakillo.github.io/R-GIS-tutorial/ Accessed March 22, 2014)

environment, most notably PySAL module (Rey and Anselin, 2010), and many spatial functions has been refactored to support parallelization (Rey et al., 2013). Free spatial data analysis packages such as GeoDa, although not open source nor extendable, offer a graphic user interface and tight coupling of GIS and exploratory spatial analysis tools (Anselin et al., 2006).

Assimilation of GIScience into other disciplines led to exciting new approaches, such as spatial ecology, spatial epidemiology, spatial history, spatial humanities, and spatial social sciences. In addition to spatial analysis and modeling, a suite of geospatial online data processing, information services and computational methods popularizes web mapping and applications. Figure 4 illustrates an example of web applications for spatial ecology research that assimilates species, ecological, and environmental data in the Gulf of Mexico (Simons et al., 2013). Location-awareness is now common in research and development in computing and information science (Hazas et al., 2004). Programming libraries are being developed to improve the integration of GIS and remote sensing (Karssenberg et al., 2007, Bunting et al., 2014). Besides mapping and visualization, these spatial turns not only provide new analytical innovations and leveraged space as a problem framing and reasoning framework but also invoked new perspectives to improve understanding in natural sciences (Rosenberg and Anderson, 2011), social sciences (Raubal et al., 2014), and humanities (Bodenhamer, 2013). It is important to make clear that these assimilating efforts are developing new spatially integrated thinking and methodologies, not just applying exiting GIS technologies in domain sciences.

Insert Figure 4 here

4.0 Future Pathways and Concluding Remarks

As spatial abstraction, algorithms, and assimilation continue evolving, GIScience thrives for multi-perspective, distributed, and collaborative research across people, platforms, and domain sciences. CyberGIS and Cloud GIS foster high performance and ubiquitous spatial computing. Both technologies not only accelerate spatial data processing but transform the ways of doing GIScience and developing GIS applications.. Wright (2012) sketched “*a post-GISystems world where GIS is subsumed into a broader framework known simply as ‘the web,’ divorced from the desktop*” in a new paradigm (p. 2197). The future of GIScience will manifest itself in the grand scheme of computational, environmental and social sciences. While time and themes are common axes along which disciplines build knowledge, GIScience distinguishes itself with the emphasis of using space as the first-order principle to acquire, organize, and compute information as well as discover and share knowledge. The distinction was already apparent in early GIS development and initial discussions on GIScience (Goodchild, 1992, Mark, 2003). It will be even more prominent in the big data era when data from location-aware devices continue to grow exponentially in volume and complexity, and spatial contextualization and integration are becoming more effective to sensing making and prediction.

The emphasis of space (e.g. spatiality, location, and situation) will continue to be the focus in pathways for future GIScience development in a world where we have access to needed information everywhere, any time, i.e. *an IEWAT world*, enabled through online-offline integration, the Internet of Things, cloud-mobile computing, collaborative information seeking and knowledge building, and integrative cyber-physical-social systems. Clearly, these are also hot topics in the broader computational, environmental and social sciences. In other words, the future pathways of GIScience are intimately intertwined with those of computational, environmental, and social sciences, and furthermore, GIScience should contribute substantially through understanding of space and use of space to achieve the vision of an IEWAT world.

Recent developments in GIScience have built strong foundations in all the three areas of spatial abstraction, algorithms, and assimilation as discussed in Section 3. The pathways forward for an IEWAT world would extend the three areas into a multiverse of a truly diverse, distributed, and collaborative nature. Every location, every person, and everything is becoming a data producer. Data are from everywhere and anytime with different ontological notions. Algorithms are being developed, coded, modified, and forked by many over the web. Information is being analyzed and synthesized dynamically and continuously to reflect real-time and near-real time situations in the environment and our society. On-line and off-line computational platforms are being transitioned seamlessly to maximize the efficiency of mobile computing anywhere and anytime. Fully integrative cyber-physical-social systems inform us of the past, present, and future of what things/people are, where they reside, how they work, how they may evolve, where we should go, and what we should do.

To date, a GIS is no longer confined in a computer system or as a software package. GIS is immersed into the greater web computing environment and heading to an IEWAT world of truly ubiquitous spatial computing. Ontological and cognitive understandings of geospatial categorization and reasoning are essential to properly conceptualize geospatial problems and realize geospatial abstractions to connect reality and GIS databases. Spatial programming, web programming, and statistical programming are essential skills to analyze data and develop geospatial solutions. Spatial analysis, spatial data mining, mapping, geovisualization and visual analytics remain critical to geospatial data exploration, information understanding and knowledge discovery. Moreover, the pathway that will revolutionize GIScience is heading to the direction in which the common mode of GIScience practices is not confined to conventional research groups but involves scientists, practitioners, and citizens in a collaborative social cloud environment. It will be an IEWAT world of the people, by the people, and for the people.

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