Chapter 5
Spatial Sciences and Research

Yingling Fan, Irene Bueno Padilla, David Haynes II, Amy Kircher, Joseph Knight, Brittany Krzyzanowski, Phil Pardey, Katey Pelican, Randall Singer, Shashi Shekhar, Eric Shook, Harvey Thorleifson, David Van Riper, and Ying Song

Abstract Spatiality—using concepts of space and place to understand patterns and processes—is found across many academic disciplines at the spatial university. This chapter outlines how spatial sciences both enhance and are furthered by work in an array of fields. It first offers an overview of the breadth of work going on at the spatial university, from arts and humanities to the social, natural, policy, and health sciences. It then provides specific examples of the spatial sciences at the university as advanced by researchers in natural resources, remote sensing, computer sciences, polar research, supercomputing, and geography and CyberGIS. The chapter then examines how a range of centers and groups are using spatial approaches to deal with topics in geology, population, urban affairs, informatics, environment, food protection, and health. We also showcase how the advancement in spatial sciences at the University of Minnesota benefits various domain knowledge areas. In sum, while this chapter can

The original version of this chapter was revised. The correction to this chapter is available at https://doi.org/10.1007/978-3-030-92847-6_7

Y. Fan (✉)
Humphrey School of Public Affairs, University of Minnesota, Minneapolis, MN, USA
e-mail: yingling@umn.edu

I. B. Padilla · R. Singer
Department of Veterinary and Biomedical Sciences, University of Minnesota, Minneapolis, MN, USA

D. Haynes II
Institute for Health Informatics, University of Minnesota, Minneapolis, MN, USA

A. Kircher
Office of Vice President for Research, University of Minnesota, Minneapolis, MN, USA

J. Knight
Department of Forest Resources, University of Minnesota, Minneapolis, MN, USA

B. Krzyzanowski
Washington University School of Medicine, St. Louis, MO, USA

P. Pardey
Department of Applied Economics, University of Minnesota, Minneapolis, MN, USA

S. M. Manson et al. (eds.), *Building the Spatial University*, https://doi.org/10.1007/978-3-030-92847-6_5

only scratch the surface in describing the range of research at the spatial university, it handily demonstrates how spatiality is central to range of important scholarship.

Keywords GISc · Spatial research · Geospatial

5.1 Introduction

Spatial science, or, more broadly, the spatial sciences, has emerged as a vital locus of research and scholarship across many disciplines. If we broaden this focus beyond the sciences to spatiality in general—in terms of using the lens of space and place to understand patterns and processes—there are few scholarly fields that fail to engage with spatial thinking. Because nothing is "nowhere" and almost everything has a spatial component, many disciplines have developed interests in spatial reasoning and spatial analysis related to the earth, physical objects, and the built environment (Baerwald, 2010). Spatial sciences contribute to the "toolboxes" of a broad range of scholarly work and creative activity at the spatial university, regardless of the underlying focus on theoretical development or empirical research.

New analytical tools, geographic information systems (GIS), and new modes of visualization have transformed the way that scientists in numerous fields conduct research. In a statement that holds true for the spatial sciences in general, the National Research Council's, 2010 report, "Understanding the Changing Planet: Strategic Directions for the Geographical Sciences," underscores the widespread and urgent need for these tools: "Many of the central challenges of the 21st century are tied to changes to the spatial organization and character of the landscapes and environments of Earth's surface as populations move, natural resources are depleted, and climate shifts. Research in the geographical sciences has the potential to contribute greatly to efforts to monitor, analyze, and prepare for these changes" (NRC, 2010).

Spatial science enables the advancement of research in multiple ways. In terms of theory building, the spatial sciences promote a special perspective and various forms of spatial thinking by incorporating place and space into a range of inquiry across many scholarly fields. Data-wise, spatial sciences enable data integration

K. Pelican
Department of Veterinary Population Medicine, University of Minnesota, Minneapolis, MN, USA

S. Shekhar
Department of Computer Science, University of Minnesota, Minneapolis, MN, USA

E. Shook · Y. Song
Department of Geography, Environment, and Society, University of Minnesota, Minneapolis, MN, USA

H. Thorleifson
Minnesota Geological Survey, St Paul, MN, USA

D. Van Riper
Institute for Social Research and Data Innovation, University of Minnesota, Minneapolis, MN, USA

between nonspatial data and spatial data, as well as the conversion of data collected at one spatial scale to other scales. Methodologically, spatial science provides analytical tools to discover patterns, suggest associations, test spatial effects, and generate knowledge about a range of phenomena.

Perhaps more importantly, the interaction between spatial sciences and the array of fields—from arts and humanities to the social, natural, policy, and health sciences—is not unidirectional. Indeed, the development of spatial sciences over time can trace their origins to natural, social, information, and health sciences. Furthermore, recent theoretical developments across the sciences have created new fields that highlight the interaction between human and environmental contexts, including ecology, social epidemiology, health geography, urban geography, and economic geography. These developments have played a significant role in motivating and promoting spatial research. The growth of spatial science has been fueled by the growing conceptual and societal recognition that space matters in understanding human and physical perspectives, alongside the emergence of new geotechnologies including GIS, global positioning system (GPS), remote sensing, surveying, and cartography that made spatial research easier.

In this chapter, we outline the increasing significance of spatial sciences and offer an overview of research fields that have contributed to the advancement of spatial sciences. We provide specific examples at the University of Minnesota, where a broad array of work has advanced many core facets of spatial sciences. We also showcase how the advancement in spatial sciences at the University of Minnesota benefits various domain knowledge areas. Note that this chapter cites to references relatively sparingly, in keeping with the broader ethos of this book to provide a broad overview. Much of the research described here is the basis for dozens upon dozens of compelling and important publications, presentations, and other forms of scholarship attached to them.

5.2 Research Advancing Spatial Science

This section will offer a general overview of the rapid growth in spatial research at the research university, with a focus on research at the University of Minnesota that has furthered the data, methods, and theories of spatial science and practice. We examine the broad range of work being funded and published on campus. We then highlight five areas of work that are directly related to the advancement of spatial sciences. They include natural resources and remote sensing, computer science and engineering, spatial research at the Polar Geospatial Center, spatial computing resources at the Minnesota Supercomputing Institute, and geography and CyberGIS work at the Department of Geography, Environment, and Society.

The University of Minnesota consistently ranks in the top ten public research institutions in the United States and had research expenditures of over 1 billion dollars in 2020. Every year, the University of Minnesota garners millions of dollars in grants with a spatial emphasis and publishes across an extraordinary range of fields

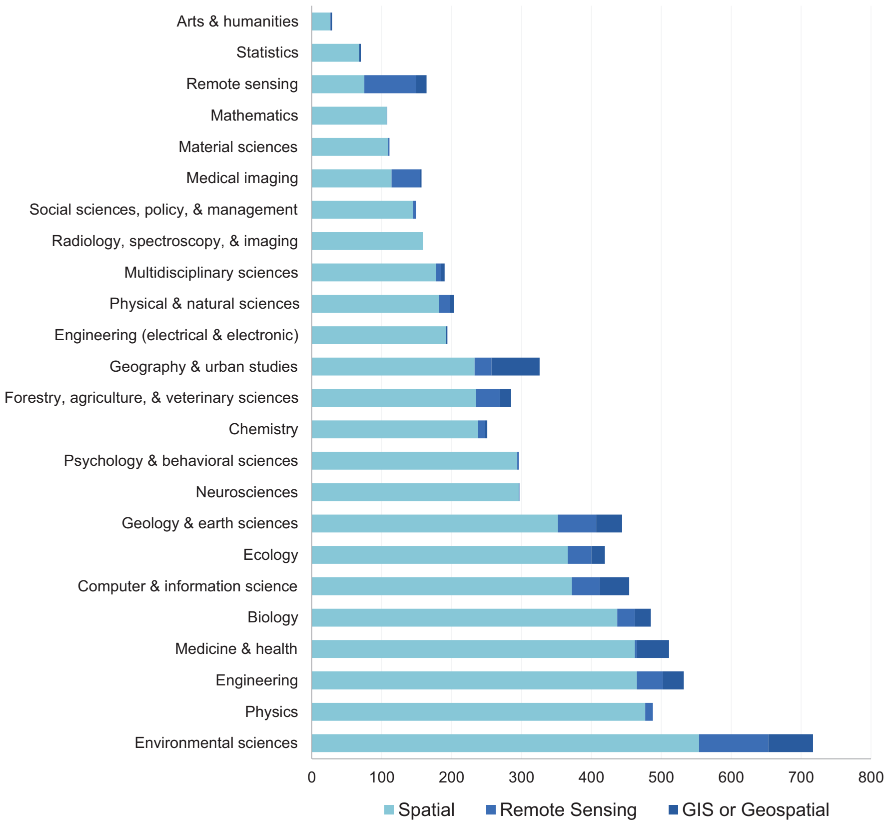

Fig. 5.1 Publications by field (2010–2020) in SCOPUS database for search terms "spatial," "remote sensing," and "GIS" or "geospatial"

(Fig. 5.1). Centers such as the Minnesota Population Center and Polar Geospatial Center host influential global spatial datasets funded in part by a range of external grants. The Institute for Social Research and Data Innovation uses a range of spatial science approaches to develop the world's largest freely available population and environment datasets. The University of Minnesota computer scientists are on the leading edge of developing new spatial science to better understand a range of social and environmental issues, such as climate change, desertification, and population growth. The Polar Geospatial Center has some of the largest holdings of remotely sensed data for researchers in the world. These and other projects highlight how the University of Minnesota hosts influential global spatial datasets that are used by thousands of students, scholars, policy makers, and other stakeholders around the world.

Beyond research dollars, the students, staff, and faculty of the university contribute to a wide array of spatial research areas. Over 2000 faculty, students, and staff engage in spatial research at the University of Minnesota. They combine spatial approaches with spatiotemporal data gleaned from maps, satellites, smartphones, sensor networks, UAV-based cameras, and social media. They help commuters to minimize travel time; farmers to best plant and protect crops; epidemiologists to identify emerging disease hotspots; emergency planners to develop smarter evacuation routes; policy makers to visualize spatiotemporal climate change scenarios; and first responders to use high-resolution imagery to map areas of need. Our faculty members have developed crucial public domain spatial software (e.g., UMN MapServer, SpatialHadoop) and have served in leadership roles for national and international societies; for example, Robert McMaster and Shashi Shekar have served as president of the University Consortium on Geographic Information Science, Harvey Thorleifson was a member of the National Geospatial Advisory Committee, Mohamed Mokbel was president of ACM SIG-Spatial, and Shashi Shekhar led a national academy workshop on spatial computing. Many other faculty members and staff have served on spatially oriented national academy committees (e.g., Mapping Sciences Committee) and boards (e.g., Board on Earth Resources and Sciences). What follows are some examples of the many high-impact and relevant spatial topics being pursued on campus.

5.2.1 Natural Resources and Remote Sensing

Research focused on the changing forests of Minnesota benefits from the rapid expansion in recent years of spatial capabilities centered on the use of remotely sensed imagery to understand many human and environmental systems. Throughout the university and the state, spatial data and methods are now ubiquitous. This broadening scope comes largely as a result of spatial research, education, and outreach done by the university. Agency partners now have skilled spatial experts on staff who are interested in expanding the use of imagery, lidar, and other spatial data in their work. Among these are resource managers and scientists at the Minnesota Department of Natural Resources' Division of Forestry and the USDA Forest Service. Some of this work can be traced back decades, as examined in Chap. 3, and in the late 1990s via Environmental Resources Spatial Analysis Center (ERSAC), which had about 20 faculty members and dozens of graduate students from multiple departments and across colleges focusing on spatial analysis of the environment (McMaster et al., 2011).

In partnership with these state and federal agencies, researchers in the Remote Sensing and Geospatial Analysis Laboratory (RSGAL), a university-wide center for remote sensing, are developing novel methods for forest health assessment and inventory. Forests are changing rapidly due to natural and anthropogenic influences. Robust methods are needed to monitor forest ecosystems, which are vital for a wide range of functions including wildlife habitat, timber production, recreation, and carbon sequestration (Knight et al., 2017). RSGAL scientists are using high-resolution lidar and infrared aerial imagery in an object-based image analysis (OBIA) context

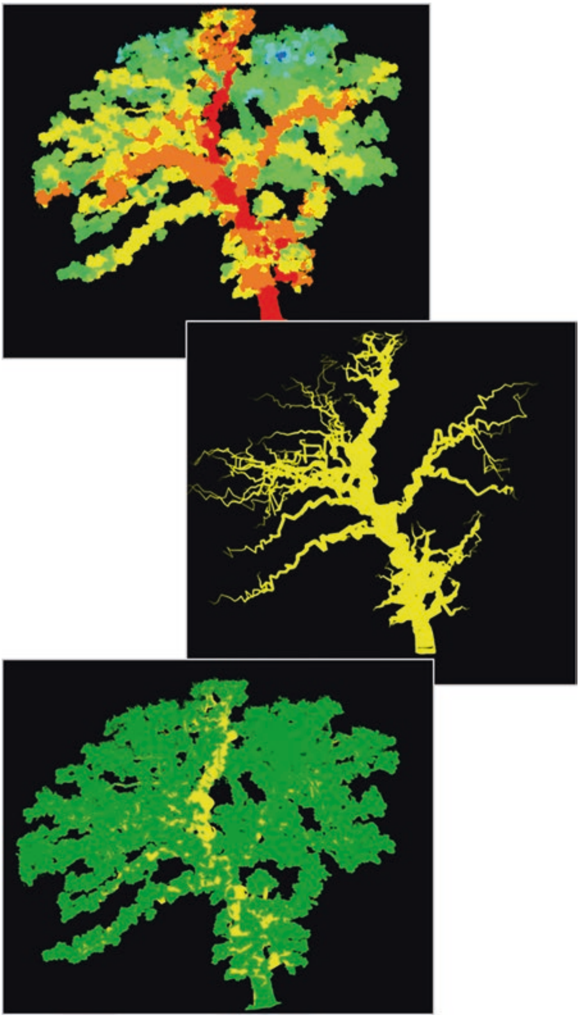

Fig. 5.2 Terrestrial Laser Scanning (TLS) image of an oak tree. From left to right, the images are the cylindrical model of the tree trunk and branches, the additional leaves and other minor branch points, and finally the reconstructed tree with stem (red) and the other colors representing branch order

to derive unprecedented detail about the structure, function, and health of our forests (Fig. 5.2).

Unlike per-pixel image analysis approaches that focus on classification of individual pixels in an image, OBIA methods delineate and classify homogeneous groups of pixels or objects using spectra, shape, size, texture, and spatial context, producing land cover classes that better approximate real-world features. These efforts integrate geospatial data from different sensors with varying resolutions and vector data. The ability to incorporate disparate data (e.g., multiple resolutions and GIS layers) into OBIA often results in higher mapping accuracy compared to traditional pixel-based classification techniques (Blaschke, 2010), which in turn makes these data better for a mix of uses.

5.2.2 Computer Science and Engineering

The University of Minnesota is a world leader in spatial computing, the term applied to a range of technologies that have transformed our lives via pervasive services such as navigation and ride-sharing apps, ubiquitous systems like the Global Positioning System, and rich scientific methods including spatial data mining (Shekhar & Vold, 2020). The Department of Computer Science and Engineering (CSE) is central to the spatial computing enterprise at the university.

CSE has made notable contributions to spatial infrastructure at the spatial university and beyond. CSE researchers also helped scale up the UMN MapServer, which was initially developed by Steve Lime when working at the University of Minnesota and in partnership with the state Department of Natural Resources as part of the NASA ForNet Project (Lime, 2008). Map Server was the first public domain software for developing spatial Web servers for analyzing satellite imagery and maps. This founding project for the Open Source Geospatial Foundation has been used to create 30,000 spatial Web servers including the NASA World Wind (a counterpart of Google Earth), which is used extensively by the scientific community. More recently, Mohammed Mokbel spearheaded development of the SpatialHadoop software system, which speeds up spatial queries on modern cloud computing platforms. It has been downloaded over a hundred thousand times by software developers around the world and influenced the design of ESRI GIS Tools for Hadoop among other projects (Eldawy & Mokbel, 2016).

In addition to advancing general spatial infrastructure, CSE scholars have developed novel approaches to a range of problems with a spatial component. These researchers have done work on responding to hurricanes and nuclear plant emergencies, including developing capacity-constrained routing planning (CCRP) algorithms, which allow policy makers and disaster response teams to develop evacuation plans. The Minnesota Department of Transportation used this work to craft evacuation plans to quickly move vulnerable populations to safety (Shekhar et al., 2012), and the Hajj Research Center (Mecca, Saudi Arabia) leveraged CCRP for emergency planning during Hajj, one of the largest global gatherings. Another standout example is the use of data-driven approaches to understanding climate and global fine-scale land cover change (Faghmous & Kumar, 2014). Finally, CSE faculty have served the spatial research community in many ways that help build the spatial capacity of other institutions. Mokbel helped Umm Al-Qura University (Saudi Arabia) and Qatar Computing Research Institute (Qatar). Shekhar served as a president of the University Consortium for Geographic Information Science and led a call for including a geospatial perspective in data science degrees and curricula. He coauthored a popular textbook on spatial databases that is used worldwide and has been translated in Chinese and Russian (Shekhar and Chawla, 2003). He also coedited the Encyclopedia of GIS, a widely used resource.

5.2.3 Polar Geospatial Center

The Polar Geospatial Center (PGC) is a federally funded center that provides geospatial support and spatial data products to the polar science community. Founded in 2007, the center's mission is to solve geospatial problems in the Arctic and Antarctic by working with researchers on mapping and remote sensing projects. Its staff works with scientists, operations staff, and military personnel, just to name a few constituencies. More broadly, it purses three broad missions: providing knowledge and expertise to address a broad range of polar geospatial problems; providing access to spatial data on the Antarctic and Arctic alongside the expertise necessary to task, manage, process, and deliver a range of products; and providing educational material and programming to transfer center knowledge and experience to the community.

PGC's primary services include a range of geospatial expertise, processing and analysis of remotely sensed imagery, bespoke mapping applications and products, and on-site support at McMurdo Station during the United States Antarctic Program Antarctic field season. The PGC User Services support team is staffed with specialists in geographic information systems, cartography, Web development, and remote sensing of various kinds. This team works with scholars from myriad fields, including astronomy, geography, glaciology, ornithology, oceanography, and operations management. Of note, in addition to the center's explicit focus on polar research, it processes other forms of remotely sensed imagery as needed. User Services have expertise in a range of geospatial fields spanning GIS, remote sensing, databases, and cartography. These staff members assist and educate the PGC users in an array of geospatial techniques and solutions. Among these are the following:

- Satellite image delivery and processing. PGC provides to the polar community access to data collected and dissemination by Maxar (formally DigitalGlobe), which offers high-resolution satellite imagery. The PGC collaborates with DigitalGlobe and the National Geospatial-Intelligence Agency (NGA) and to coordinate imagery acquisition and processing these data for delivery to PGC users.
- GIS data and maps. The PGC curates and disseminates a variety of other geospatial data beyond just remotely sensed imagery, including historic and current maps, aerial photography, digital elevation models such as ArcticDEM, and lidar collections of the McMurdo Dry Valleys.
- GIS analysis and mapping. The center offers assistance in spatial analysis and modeling to researchers, including custom mapping based on its extensive archive of maps and spatial data on the Arctic and Antarctic.
- Seasonal on-site support at McMurdo Station. During the United States Antarctic Program (USAP) Antarctic field season, PGC staffs an office at McMurdo Station to provide on-site support to science and operations personnel. Because research resources and Internet bandwidth are limited in McMurdo, PGC will often perform work in support of users in advance of the field season in addition to in situ support.

The center is housed in the Department of Earth and Environmental Sciences in the College of Science and Engineering. It receives most of its funding from the National Science Foundation (NSF), National Geospatial-Intelligence Agency (NGA), and National Aeronautics and Space Administration (NASA), although the University of Minnesota also provides support in various forms. Over its near two-decade history, the center has provided geospatial support to hundreds of research groups and their academic activities along with engaging with a wide range of constituencies outside of the academy, ranging from K–12 groups to policy makers.

5.2.4 Minnesota Supercomputing Institute (MSI)

Minnesota Supercomputing Institute (MSI) is one of the oldest supercomputing institutes in the United States. It has advanced research at the University of Minnesota for over 30 years and continues to provide computational and data-intensive resources and expertise to advance research across the university. Operating as part of Research Computing in the Office of the Vice President for Research provides MSI broad reach across the university as well as tight integration with other units in Research Computing, including the University of Minnesota Informatics Institute (UMII) and U-Spatial.

Spatial research has been a growing area for MSI in recent years with active research in remote sensing, satellite imagery, data science, and deep learning. MSI provides unique resources for spatial research, including interactive computing, a visualization studio for massive display of geospatial information, and several compute- and data-intensive resources for processing, analyzing, and visualizing spatial data. To help interface with the growing need in spatial research, MSI has a dedicated HPC Geospatial Analyst as part of their Research Informatics Solutions group. Through combining computational resources and expertise, MSI is an important component of any spatial university, providing the computational backbone to support advances in geospatial technology development and creating advanced geospatial infrastructure including spatial databases, spatial data science, and geospatial computing.

5.2.5 Geography and CyberGIS

Geography is a dynamic and growing field, with intellectual connections that ramify across the liberal arts and the natural and applied sciences. Established in 1925, the Department of Geography, Environment, and Society (GES) is one of the oldest and most respected geography programs in the United States and consistently ranks among the top geography programs nationally. In recent years, GES faculty have received multiple major research grants in the spatial sciences from the NSF and NIH. GES has always been well known as an innovative place for GIS and spatial analysis more generally, much of which inherits from the work of Borchert and others who built the department.

The department has several areas of focus. As outlined in Chap. 3, the department has long been a leader in cartography and visualization. Mark Lindberg, Susanna McMaster, Robert McMaster, Ying Song, and Di Zhu all work on solving research challenges in cartography and visualization, ranging from advancing the state of art in generalizing maps to work that identifies how to best represent complex spatiotemporal patterns and processes in contexts ranging from human transportation to animal movement. For example, Lindberg studies cartography with a strong psychological element—in the sense of drawing on decision-making research on how people perceive maps—that adapts to vagaries of real-world map production.

The department also does much work with global data and challenges. Steven Manson, Eric Shook, and Kathryn Grace collaborate with the Minnesota Population Center, Institute on the Environment, and Libraries to conduct scholarship that integrates the social science of population and environmental science of global change. This work is related to that in health and population, where a number of scholars work in topics around health and population, from how rainfall affects human well-being in Mali and Ethiopia to using big data to map and predict the spread of disease in the global south. Grace's work, for example, examines the role of context in maternal and child health via a quantitative, mixed disciplinary approach to the examination of the way that individual and household outcomes are conditioned by culture and the natural environment.

The department has a history of scholarship on how society interacts with GIS, with former colleagues including Eric Sheppard, Helga Leitner, Howard Veregin, and Francis Harvey joining current faculty in advancing understanding of how maps contribute to, and are conditioned by, social dynamics. In this vein, Susanna McMaster researches professional GIS education alongside the history of academic cartography. Finally, the department does much work in big data and data science, with Manson, Shook, and Zhu all working to address the challenges of advancing the data, method, and theory of using large datasets to tackle a range of human-environment topics including agriculture, deforestation, and global pandemics.

5.3 Spatial Science in Service of Discovery

In addition to a broad array of work on advancing the data, methods, and theory of spatial science as such, the university is home to a vast array of work that uses spatial science approaches in service of domain knowledge. We highlight seven domain areas in which the advancement of spatial sciences has benefited the knowledge discovery process. They include geological mapping in the Minnesota Geological Survey, spatial research at the Natural Resources Research Institute, urban research at the Center for Urban and Regional Affairs, data-driven agriculture innovation at the GEMS Informatics Center, demographic research at the Minnesota Population Center, ecological research at the Institute on the Environment, food system research at the Food Protection and Defense Institute, and health and medical research across the university.

5.3.1 Minnesota Geological Survey

Throughout the world, geological survey agencies mandated by government maintain the systematic, jurisdiction-wide subsurface mapping, monitoring, and research that is needed for government and society to function optimally in fields such as water, energy, minerals, hazards, and engineering. As with other federal systems, the United States has a federal survey—the United States Geological Survey (USGS), which has a budget of greater than $1B and approximately 9000 employees—and state geological surveys that presently receive total annual funding of $241 M and have over 1840 employees. About a third of the state geological surveys are based in universities. The Minnesota Geological Survey (MGS), established by the Legislature as part of the University of Minnesota in 1872, has been located off campus in St. Paul since 1970. It has an annual budget of $3.3 M and a staff of 38 that has grown by 30 percent over the past decade. MGS priorities have been specified by a series of broadly consultative state resource planning exercises. For example, in 2011, the Minnesota Water Sustainability Framework advocated that a measure of progress in obtaining a picture of groundwater resources—our principal source of drinking water—should be the rate of completion of county geological atlases. The framework advocated for geological atlases, which are prepared by MGS and the Department of Natural Resources (DNR), to be completed at a much faster pace.

County Geologic Atlases (CGA) provide information essential to sustainable management of groundwater resources for applications such as aquifer management, groundwater modeling, monitoring, permitting, remediation, water allocation, well construction, and wellhead protection. The atlases define aquifer properties and boundaries, as well as the connection of aquifers to the land surface and to surface water resources. They also provide a broad range of information on county geology, mineral resources such as construction materials, and natural history. The atlases thus are also useful to consultants, exploration efforts, educators, and the public. A complete atlas consists of two parts: Part A prepared by MGS that includes the water well database and 1:100,000 scale geological maps showing properties and distribution of sediments and rocks in the subsurface, and Part B, constructed by the DNR, which includes maps of water levels in aquifers, direction of groundwater flow, water chemistry, and sensitivity to pollution. Atlases in most cases are initiated by a request from a county and an offer to provide in-kind service. A User's Guide to Geologic Atlases helps non-geologists understand the information products and their uses. Atlases are available in print or in digital formats, including PDFs and GIS files. Atlases are complete for 41 counties, and of these, 5 have been revised and 2 revisions are underway. There are 23 new atlases underway; 21 counties have not yet been started. At the current pace and a completion rate of approximately 5 per year, statewide coverage will be achieved in less than a decade from now.

The County Geologic Atlas program is the key to the broader MGS plan to fulfill a range of user needs. It does so primarily through mapping of geology, bedrock topography, and sediment thickness. This geological mapping is first published as authored and peer-reviewed geological maps but is also being assembled as a two-resolution (1:100,000 and 1:500,000) layered set of databases that includes the off-shore region that underlies bathymetric and soil mapping, and that is as compatible as possible with neighbors. MGS is producing progressively more seamless geological areas that increasingly show properties, heterogeneity, and uncertainty. A layered 1:500,000 state bedrock geological map is now complete, with mapping of thickness and underlying geology for Precambrian layers completed in 2020, along with a new state Quaternary geology map in 2019. This geological mapping is accompanied by associated spatial databases. The publication database, which is spatial through publication footprints, includes over 50,000 pages and 700 scanned maps, both searchable and Web accessible. These geological databases include a range of field observations and geological collections. MGS coordinates with the DNR drill core library and mineral exploration document archive, the Bell Museum fossil collection now stored in Ohio, and the DNR aquifer properties database. In sum, the MGS has long offered a range of data collection and mapping services as a core part of the spatial university in terms of data and workflows as well as to meet the needs of many individuals and groups in the state across the private and public sectors.

5.3.2 GEMS Informatics Center

Agriculture is a spatially sensitive production process. Productivity performance of the sector depends heavily on precisely where, and when, on the planet agriculture takes place. And it is deeply intertwined with spatially variable environmental attributes such as soil, water, and sunlight. The University of Minnesota's GEMS (named for Genetics, Environment, Management, Socioeconomic) informatics initiative, launched in 2015, is a novel, joint venture between the College of Food, Agricultural, and Natural Resource Sciences (CFANS) and the Minnesota Supercomputing Institute (MSI) designed to catalyze a data-driven revolution in food and agriculture. To do so, GEMS developed and operates the GEMS informatics platform, a standards-based analytics and data sharing system. The platform is built using open-source tools, is geospatial by design, is respectful of intellectual property, and expedites the analysis of big (and little), disparate, and sometimes messy data. GEMS services encompass four main program areas: secure data storage, sharing, and analytics platform; Internet of Things (IoT) data collection systems; Application Programmer Interfaces (APIs) for on-demand GxExMxS (genetics x environment x management x socioeconomic) data, modeling, and analytic products; and GEMS external consulting and advising services.

- GEMS secure data storage, sharing, and analytics platform. GEMS services include a secure data sharing and analysis platform that enables interoperability across data holdings by fostering the usage of international metadata and ontology standards. Additional data processing features include metadata management, auto-versioning of data files, and the associated workflow approach that is taken to ensure information products are replicable. During data ingest, platform users can tap an array of data outlier detection and cleaning tools, including those specifically designed to identify and rectify spatial data. An important attribute of the GEMS platform is its secure storage and smart sharing capabilities that support the ethical use of data subject to data privacy or security concerns (drawing on the work of James Wilgenbusch and others in the University of Minnesota's Research Computing). Users of the platform can choose to make their data openly available, keep their data private, or share with any combination of teams or individuals. Importantly, metadata can be shared separately from the data itself, allowing users to make their data discoverable or share the data itself via their own click-through licenses. The platform also includes a range of anonymization tools that enable sensitive data (including, e.g., georeferenced farm level data) to be kept private while an internally linked, anonymized version of that same data can be shared more widely at the data provider's discretion. The GEMS platform can be federated, with an on-site instance of the platform now operating at Stellenbosch University, South Africa, in addition to its core hub at MSI's supercomputing facilities in Minneapolis.
- GEMS-IoT data collection systems. GEMS has a continually evolving Internet of Things (IoT) offering that provides affordable, multi-sensor deployments that stream data directly to the platform. These sensing systems (and their associated back-end data pipelines) have been deployed on four continents, including across Minnesota and Malawi. Part of the configuration in Minnesota is being implemented in an explicitly spatially aware fashion across the University of Minnesota's Research and Outreach Centers (ROCs), thus providing an integrated network of electronic infrastructure that enables digital agricultural discoveries across highly diverse agroecologies and agricultural production systems.
- GEMS APIs for on-demand GxExMxS modeling and analytics. In parallel with the analytic and data collection capabilities on the GEMS platform, users also have the option to subscribe to a range of Application Programming Interfaces (APIs), which allow them to query complimentary streams of data that have been predesigned to be spatially and temporally interoperable. The API infrastructure allows other platforms to exchange data with the GEMS platform, empowering remote scientific workflows. Thus, GEMS makes an ideal back end to widely flexible visualization front ends.
- GEMS external consulting and advising services. Even with the many offerings that GEMS provides, collaborators and clients find it useful to create custom projects. GEMS personnel consult with numerous companies, private nonprofit corporations, and government agencies. These professionals include experts in systems administration, software development, network security, machine learning, data science, plus domain science expertise in genetics and agronomy,

Geographic Information Science (GISc), spatial econometrics, environmental modeling, and other areas. GEMS staff work with organizations including private companies such as PepsiCo; a range of private foundations and nonprofits including the Rockefeller Foundation, Soil Health Partnership (SHP), One Acre Fund, and Land O′ Lakes Venture37; and government agencies such as the USDA's Foundation for Food and Agriculture Research (FFAR). Further, GEMS has designed data and software systems specifically for other consortia including Genomes2Fields (G2F, funded by Iowa Corn), which includes collaborators from more than 20 states throughout the nation.

GEMS operates with innovation partners across campus and throughout the world to integrate spatial data, thinking, and analytical tools. For example, GEMS has developed and operates a flexible spatial tile indexing system to streamline access to and analytical use of geospatial remote-sensed data from various remote sensing platforms. In partnership with the university's InSTePP (International Science and Technology Practice and Policy center), GEMS has a multifaceted program of spatially explicit, bio-economic modeling, including, for example, workstreams to measure and assess the spatial movement of agricultural production. GEMS has developed and implemented workflows that assess, in a probabilistic, spatially explicit fashion, the bio-economic implications of crop pests and diseases (Pardey et al., 2013). Partnering with the Minnesota Invasive Terrestrial Plants and Pests Center (MITPPC) at the university, GEMS is drawing on MSI's supercomputing capabilities to also stand up a flexible pest dispersal simulation system that models climate and human-mediated crop pest dispersal at multiple spatial scales. MSI's resources have also been used to train locally developed models that use historic weather and soil conditions to predict with high-accuracy yield and high-quality traits for arbitrarily selected crop variety genotypes in desired planting locations. A significant workstream is also being developed to power real-time, distance-to-market analytic pipelines that inform myriad decisions by multiple public and private parties. These in turn affect the cost-effective access to outputs produced on farm and production inputs used by farmers. Spatially aware market access information is a particular challenge for those farms and agribusiness seeking to innovate in developing countries with fragile rural infrastructure systems. In sum, GEMS leads the way in integrating spatial data and methods into a broad array of research and policy.

5.3.3 MPC and Spatial Analysis Core

The Minnesota Population Center (MPC) hosts the Spatial Analysis Core and plays a key role supporting spatial research across the university. The MPC was established in 2000 with a grant from the National Institutes of Health (NIH) to, among other tasks, curate and disseminate large-scale population datasets (Sobek et al., 2011). Development of a major spatial data infrastructure project and recognition that numerous groups at the University of Minnesota required spatial research support precipitated development of the Spatial Analysis Core in 2006. In 2018, the MPC served as the foundation for the Institute for Social Research and Data Innovation, an interdisciplinary research institute within the university that provides the infrastructure and services to four centers within the institute: IPUMS, the Minnesota Population Center, the Life Course Center, and the Minnesota Research Data Center.

The MPC received a $5 million grant in 2001 from the NSF to create the National Historical Geographic Information System (NHGIS). The initial vision of NHGIS was a Web-based data access platform providing aggregate census data and GIS-compatible mapping files from 1790 to the present (Fitch & Ruggles, 2003). While a large portion of the historical aggregate census data was in digital form by that time, relatively little GIS data existed that depicted historical states/territories, counties, or census tracts. Many people, including a large number of undergraduate and graduate students working alongside full-time staff, created these mapping files and incidentally built a critical mass of people with strong spatial skills that would serve as the nucleus for the core.

Recognizing the importance of the spatial capacity developed through work on NHGIS, the MPC established the Spatial Analysis Core in 2006 when it received renewed NIH center funding. The core, directed by Pétra Noble from 2006 to 2010 and David Van Riper from 2010 onward, provided support for spatial analysis to students, staff, and faculty who were MPC members. This support ranged from the acquisition or creation of spatial data to the development and execution of complex spatial analysis tasks to training in basic GIS skills. For example, the core provided support for numerous research projects in the School of Public Health exploring the relationship between obesity, the built environment, and the food environment. Core staff geocoded participant addresses and constructed egocentric measures of the built or food environment surrounding the addresses. These personnel also worked with faculty and staff to enrich participant data with information describing the demographic and socioeconomic characteristics of their neighborhoods.

When U-Spatial was established in 2011, it took over a number of the services from the Spatial Analysis Core, but the core continues to support the spatial analysis needs of MPC members. The core also plays a key role in a number of data infrastructure products, including IPUMS NHGIS, IPUMS USA, and IPUMS International, developed and maintained by the Minnesota Population Center. IPUMS NHGIS offers harmonized US Census data for 1790 onward and is the largest publicly accessible population database in the world, while IPUMS International is the largest international population database in the world, covering much of the world and over half a billion individuals described by hundreds of billions of data points. Both projects require a good deal of spatial science support through the data collocation, collation, curation, and dissemination. In particular, core staff create GIS files delineating the administrative and statistical units represented in the data, and they create customized geographic variables that increase data utility. For several years, U-Spatial and the Spatial Analysis Core shared the same space, which helped both units grow—so much so that they needed their own bigger spaces—but the two groups still communicate and work together regularly to advance the mission of the spatial university.

5.3.4 *Institute on the Environment*

As noted throughout this volume, there is an extraordinary amount of spatially informed research happening in ecology and cognate environmental fields. In addition to stand-out examples noted above, work at the University of Minnesota's Institute on the Environment exemplifies spatial research with an ecological focus. Several projects stand out in particular: the Global Landscapes Initiative, the Global Water Initiative, and the Natural Capital Project. While all three see themselves primarily as human-environment projects, all are built in part on a foundation of spatial science approaches.

The Global Landscapes Initiative researches, develops, and applies approaches to characterize global land use, although it touches on land cover as well. The overriding goal of the initiative is to understand human land-change, particularly trends in global agricultural supply and demand and underlying facets of the land use, including cropping and its many inputs (fertilizer, water, labor) and outputs (food, fiber, fuel). This work is also designed to improve how people balance human needs met by land use with environmental impacts. Much of this work is inherently spatial but happens outside of what many people consider standard workflows for GIS, using a mix of programming and mathematics in approaches closer to physics and other natural sciences. In addition to supporting publications in high-profile venues, GLI is focused on making available public-facing publications including Environment Reports hosted at the Institute on the Environment and data via the EarthStat (EarthStat.org) for other researchers and policy makers around the globe at a range of institutions including National Geographic, ESRI, CGIAR (formerly the Consultative Group for International Agricultural Research), the Inter-American Development Bank, the American Museum of Natural History, and others. Figure 5.3 shows one of the project's most popular products, the 2000 cropland layer, which shows croplands and pastures for around the turn of the century derived from agricultural inventories and satellite-based land cover data at a spatial resolution of about 10 km.

The Global Water Initiative uses spatial science approaches in combination with other methods to evaluate water sustainability and help develop tools that help water managers. Some of this work centers on mapping water use, availability, and scarcity at various scales around the world and exploring potential effects shifts in water use and supply. Lead researcher Dr. Kate Brauman worked with staff at the Institute on the Environment and partners with the Global Water Policy Project, the Nature Conservancy, and the Center for Environmental Systems Research at the University of Kassel in Germany to create a water scarcity map. This product set a new bar for understanding water availability (especially where there is insufficient water to meet demand) around the globe at a much finer resolution than previously available.

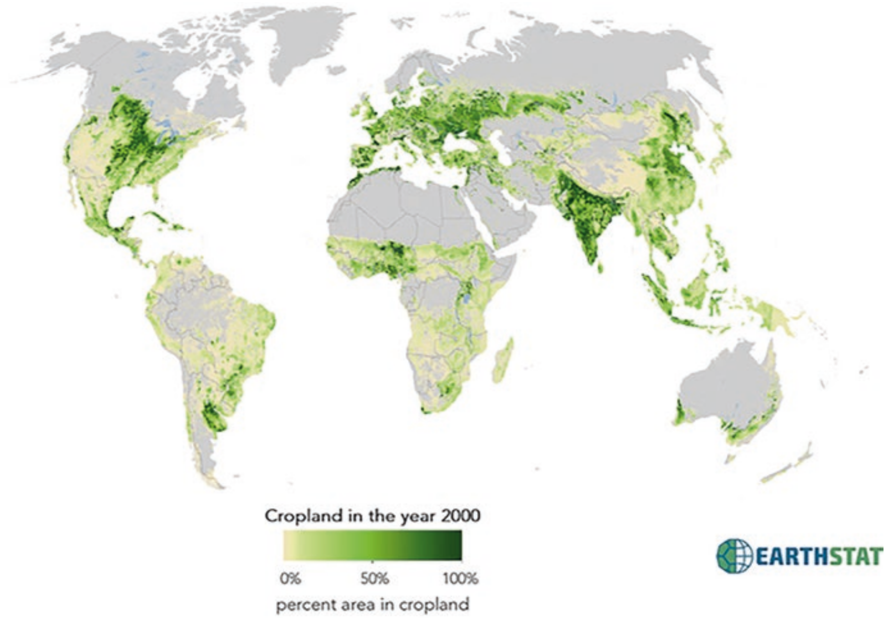

Fig. 5.3 Global Landscapes Initiative global cropland layer

In addition to better spatial resolution, this product also recognized the impacts of seasonal and annual shifts in the water availability.

The Natural Capital Project is a decade-long partnership among the University of Minnesota, Stanford University, the Nature Conservancy, and the World Wildlife Fund. This project is interested in better understanding and modeling ecosystem services or the many ways in which nature provides humankind with a range of goods and services including clean air, fresh water, and food. The project has several focal areas within its broader remit: human well-being and valuation, land use change, livable cities, visualizing trade-offs, and advancing the case for sustainability standards. Many of these areas are addressed through the lens of spatially and temporally assessing ecosystem services. Much of its work focuses on assessing and projecting the ecosystem impact of land use change such as agriculture and forestry on water and soil provision. These models can drive sophisticated visualization that a range of stakeholders better understand how a mix of human actions can bear on a range of ecosystem services. While the project has a global reach, it has been integral to advancing local projects, including providing tools to model the impacts of conservation easements (such as placing crop land into long-term forestry projects) and to assess the threats to water quality in the state from future climate change.

5.3.5 Food Protection and Defense Institute

The Food Protection and Defense Institute (FPDI) at the University of Minnesota is an Emeritus DHS Center of Excellence founded in 2004. FPDI was established to provide research, education, and technology development to enhance the ability to protect the food supply from disruption to include an intentional attack. The knowledge and tools generated from FPDI's work have been used by numerous agencies and organizations around the world—including US agencies (DHS, USDA, FDA, FBI, and CDC), foreign governments, and the United Nations—in their regulation, public health, trade, law enforcement, and homeland security and missions. In addition, numerous companies in the food industry have also benefited from using FPDI's expertise and tools to better understand their food protection-related risks, threats, and mitigation needs and to implement food defense practices.

FPDI uses spatial science approaches to enable collaboration with myriad stakeholders to tackle complex issues. Protecting the food supply from intentionally caused harm is a uniquely challenging endeavor for several reasons. First, almost all of this critical infrastructure is owned by the private sector where information is not widely shared. Second, in the United States, 14 federal agencies have food safety responsibilities, and several more have responsibilities for responding to intentional contamination events. Finally, all state and territorial governments and many local ones have significant food-related public health jurisdiction. Negotiating the overlapping, sometimes poorly defined, and/or conflicting food, trade, and critical infrastructure rules and regulations among these stakeholders is a highly complex and challenging responsibility requiring significant collaboration among many partners to illuminate and mitigate food system challenges (e.g., food safety issues, intentional adulteration).

The institute also applies geospatial capabilities to protect the food system. A wide range of natural or man-made events, including natural disasters, political instability, and market fluctuations, may disrupt supply and incentivize intentional adulteration. While data exists to monitor these risk factors, optimal use of this information by government and private industry is hindered by sheer amount of data that must be reviewed. To address finding signals within vast quantities of data sources and systems, FPDI developed the Focused Integration of Data for Early Signals (FIDES) platform to curate and make sense of this data to support "horizon scanning" of potential food system disruptions. The FIDES Web application fuses multiple streams of data from disparate sources and displays information in the form of an online geospatial dashboard where users browse, search, and layer dynamic and reference datasets related to disruption events. Visualizing fused data geospatially highlights food disruption patterns, cascading effects of natural disasters (e.g., typhoons, infectious disease), and illuminates supply chain challenges that create food system issues as a result of natural (e.g., weather) or man-made (e.g., piracy) events. FIDES has been employed in support of intergovernmental organizations, government agencies, and private industry to rapidly identify and mitigate the impact of catastrophic or intentional contamination events. Examples of data currently included in FIDES are import refusals, global disasters, animal health alerts, food defense incidents, historical food safety incidents, import data, price alerts, and reference data on food production worldwide.

5.3.6 Spatial Science and Health Research

We turn to the health sciences for a final example of how spatial sciences are helping advance domain knowledge, specifically our understanding of public health, nursing, medicine, health informatics, and veterinary science. Epidemiology has been incorporating spatiality into its study since the nineteenth century and continues to advance spatial science more generally today. Anesthesiologist John Snow's 1854 investigation of a cholera outbreak in London is popularly referenced in almost every introductory-level epidemiology course given its relevance to communal and environmental health. By mapping cholera deaths in the area, Snow (often considered the founder of epidemiology) was able to determine the cause of the cholera outbreak to be a contaminated water pump. Several versions of the story exist, and its historical significance has been called into question, but Snow's work remains a popular way to bring together social and geographical concepts into the conversation of population health. Modern social epidemiology considers the interplay between individual-level genetic vulnerabilities and population-level social determinants of health while also underscoring the role of place. Where we live; the conditions in which we work and go to school; place-based differences in climate, environment, policy, and discrimination; and the impact of history and culture at each and every level all paint a clearer picture of how health and disease encapsulate the human experience.

Scholarship at the University of Minnesota leads the way in exploring how space can be integrated into models of health and disease. In the School of Public Health, researchers look at a wide range of topics spanning from heart disease to depression to substance abuse, all of which greatly benefit from spatial perspectives. There are many examples of public health research groups on campus taking advantage of existing spatial technologies to explore topics of health. For instance, public health researchers Austin Rau, Jesse Berman, Jonathan Oliver, and Claudia Muñoz-Zanzi used mapping tools to examine the spread of tick-borne diseases in the neighboring state of Wisconsin. Another public health research team working with U-Spatial investigated population health in Lorain County, Ohio, by using multi-resolution land cover imagery to derive heat vulnerability to assess the impact of climate change on cause-specific mortality. More broadly, Michael Oakes in the Division of Epidemiology and Community Health coedited *Methods in Social Epidemiology* (Oakes & Kaufman, 2017) and uses spatial approaches that capture the interplay of individual, household, and neighborhood health dynamics. Scholars in the Division of Biostatistics focus on developing statistical methods, including spatially aware approaches, for biomedical research related to topics including communicable disease, cardiovascular and pulmonary disorders, cancer, and neuroimaging. Finally, scholars across the university used spatial approaches to address the COVID-19 pandemic, including developing disease maps and planning responses such as optimal spacing of classrooms and other spaces to enable social distancing.

In the School of Nursing, researchers have been integrating spatial analysis into their work as well. Madeleine Kerr, Associate Professor Emerita, led and coled several projects that relied on GIS and spatial analysis to examine various aspects related to the discipline of nursing. For example, Kerr first collaborated with U-Spatial to create a mapping project so that students could collect and map data using the World Health Organization's age-friendly cities checklist (Kerr et al., 2016b). Next, Kerr and nursing students organized the creation of a crowdsourced Web map to assist nursing colleagues working on the ground in Liberia during the Ebola crisis. Later, Kerr collaborated with U-Spatial, Karen Monsen, University of Minnesota professor and coordinator of the DNP Nursing Informatics specialty, and Carol Flaten, University of Minnesota clinical associate professor, to create a windshield survey mapping project as a follow-up to their international study using windshield survey methods and the Omaha System standardized terminology to describe community observations (for an example, see Kerr et al., 2016a). In a follow-up project, students at the University of Minnesota and the University of Auckland New Zealand mapped their observations of community strengths and challenges using ArcGIS online. More recently, in order to further encourage spatial research within nursing, Kerr and Monsen led intensive workshops to provide nursing informatics students with research training in GIS methods.

The School of Medicine has also taken advantage of the abundance of spatial analytical resources and research support on campus. For example, U-Spatial RAs assisted the Minnesota Heart Health Program with the Ask About Aspirin community intervention trial by using mapping software to build custom control and treatment sites that were exchangeable in population demographics (Krzyzanowski et al., 2019). Related research in the University of Minnesota's Variety Club Research Center (VCRC) investigated the geographic distribution of peripheral arterial disease (PAD) and major adverse cardiovascular and limb events among Medicare beneficiaries. Within the Pediatrics Department, Pui-Ying Iroh Tam collaborated with U-Spatial and the Geography Department to conduct the geographical analysis for a retrospective cohort study that examined the role of social and environmental determinants on pneumonia hospitalization risk (Tam et al., 2017).

The Institute for Health Informatics has also grown to integrate the application of spatial methods and geographic concepts to health data. For example, David Haynes led a team to explore ways in which they could address the lack of spatial computation, exploratory data analysis, and spatial data exploration tools available within public platforms by creating a Spatial Online Analytical Platform (SOLAP). SOLAP uses a user-interface and user experience design approach to integrate spatial analysis tools that allow users to explore and learn more about spatial patterns of COVID-19. On a separate project, the Institute for Health Informatics collaborated with the Minnesota Department of Health to explore small area mapping techniques to understand disease prevalence for sparsely populated areas and small geographies (i.e., a city block). The team used novel methods to estimate breast cancer screening rates for the state of Minnesota at fine spatial scales (Hughes et al., 2021). This approach offered policy-relevant insights necessary for better planning of testing locations and dealing with the vagaries of how administrative boundaries are drawn. Another project out of the institute explored use of a mobile app, Smart Community Health (SCH), that connects people with social care needs to local community resources via health screening, self-referrals, real-time registration and modification of services, and real-time visualization and analytics. This platform improves the ability for patients and health-care providers to improve a patient's well-being and exemplifies, with the other projects noted, how health informatics can drive forward the spatial university.

The School of Veterinary Medicine also integrates widely available campus spatial analytical resources within their work. For instance, a research team associated with the Minnesota One Health Antibiotic Stewardship Collaborative (MOHASC) examined the role of the natural environment in the emergence and dissemination of antimicrobial resistance (AMR). The project was designed to predict environmental "hotspots" of antibiotics and antibiotic-resistant genes (ARG) by combining field data with geospatial modeling. Spatial tools and methods were key to identifying the spatial distribution of antibiotic and AMR sources in the natural environment of Minnesota; designing the study at two different spatial scales (macroscale and microscale); capturing the field data in an easy, coordinated fashion with the Collector app; and analyzing spatial patterns to predict areas with higher antibiotic concentrations and ARG abundance (Bueno Padilla et al., 2017). In addition to research on AMR and ARGs, researchers with the Center for Animal Health and Food Safety in the School of Veterinary Medicine collaborated with multiple stakeholders in Minnesota to explore the application of spatiotemporal tools when informing decisions related to health. This work explores the process of cocreating knowledge where researchers and stakeholders could work together to improve data quality, surveillance, and preventive measures in epidemiological studies addressing a range of health issues.

More importantly, interdisciplinary health teams have formed on campus, and these groups are well suited for the uptake of spatial methods in their research. One particular interdisciplinary health research team working together for the University of Minnesota's Global One Health Initiative created a One Health Mapping and Analysis Resource Toolkit (OH-SMART) for community infectious disease preparedness. The OH-SMART Toolkit is best seen as an interactive process that helps guide research across organizations responding to disease outbreaks or responding to other complex health challenges by assisting with coordination, response planning, and team development. Another related example is the broader team-building aspects of One Health. Pelican and others (2020) describe a number of case studies of building One Health leadership and team building in locations around the globe, including Indonesia, Vietnam, Minnesota, and over a dozen countries in Africa. In all of this work, the research mission of the spatial university is advanced by building teams that can enact values of trust, innovation and adaptability, systems base problems solving, support mobilization, and modeling helpful behaviors.

Some of the University of Minnesota scholarship at the intersection of spatial science and health have led to patents and technology commercialization. For example, Yingling Fan and her collaborators have patented and commercialized an app-assisted day reconstruction tool that combines mobile sensing with human input to accurately and comprehensively measure human behavior and well-being with minimal respondent burden. The novelty of the app is twofold: (1) the use of spatio-temporal machine learning algorithms to reconstruct daily time use (activity) and spatial movement (trip) episodes from mobile sensing data in real time and (2) the use of a well-designed user interface to acquire additional self-reported data on the auto-constructed daily activity and trip episodes such as emotional well-being. The technology, initially called SmarTrAC and later named Daynamica, was granted a US patent titled "Travel and Activity Capturing." A year later, Fan and her collaborators founded Daynamica, Inc. with the help from the University of Minnesota Venture Center. Figure 5.4 illustrates the main user interface of the Daynamica app, which is currently available as both an Android and IOS application.

The Daynamica app has been deployed in a wide range of research studies across the United States to collect spatial movement, time use, and well-being data (e.g., Fan et al., 2019; Le et al., 2020). Recently, Daynamica, Inc. has expanded the capabilities of the application by integrating physical activity and biometric data from wearable devices and developing the capability to deliver context-sensitive behavior interventions within the application. The Daynamica team has also developed a HIPAA-compliant version of the app that is currently being trialed in two medical research studies at the University of Minnesota.

5.4 Conclusion

The above review of the spatial science-related work at the University of Minnesota shows that the interaction between spatial sciences and natural/social sciences is not one-directional: the development of spatial sciences traces its origins to natural and social sciences and at the same time contributes to the advancement of natural and social sciences. It is not surprising that employment opportunities relating to spatial science have grown explosively over the past few decades. Spatial science is a useful lens with which to study many research topics that concern the earth and its people. Across many disciplines, the importance of spatial thinking skills—the ability to place problems and objects within the space dimension and reflect on the spatial relationships between problems and objects—has been widely acknowledged. For modern research universities such as the University of Minnesota, it is increasingly important to strengthen investments in spatial science-related infrastructure that could not only serve but also drive a fast-growing need for expertise in GIS, locational sensing, and spatial computing across a diverse range of natural and social science disciplines.

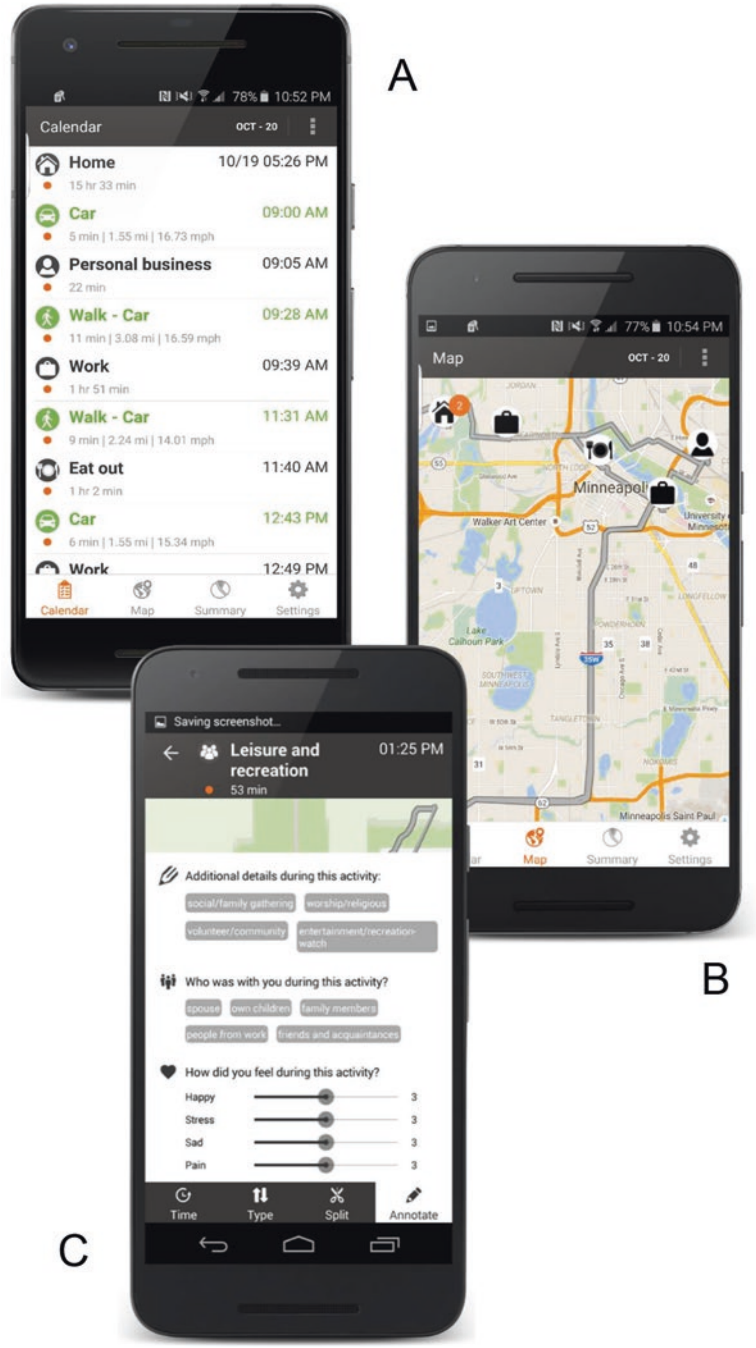

Fig. 5.4 Daynamica main interface. Daynamica constructs the activity-trip sequence in real time from mobile sensing data, inferring activity/trip start/end time, activity type, and trip mode (**a**). It captures and displays detailed spatial information (**b**). Users can confirm or correct the activity/trip information and provide additional details (**c**)

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