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Perspective

GIScience and remote sensing in natural resource and environmental research: Status quo and future perspectives

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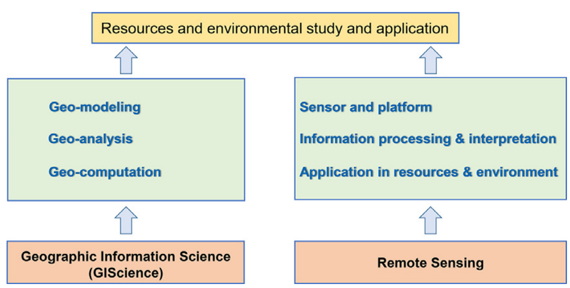
HIGHLIGHTS

- Clarify the definitions and frameworks of GIScience and remote sensing (RS)
- Discuss the roles of GIScience and RS in natural resource and environmental science
- Forecast future directions for remote sensing and GIScience

GRAPHICAL ABSTRACT



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ABSTRACT

Geographic information science (GIScience) and remote sensing have long provided essential data and methodological support for natural resource challenges and environmental problems research. With increasing advances in information technology, natural resource and environmental science research faces the dual challenges of data and computational intensiveness. Therefore, the role of remote sensing and GIScience in the fields of natural resources and environmental science in this new information era is a key concern of researchers. This study clarifies the definition and frameworks of these two disciplines and discusses their role in natural resource and environmental research. GIScience is the discipline that studies the abstract and formal expressions of the basic concepts and laws of geography, and its research framework mainly consists of geo-modeling, geo-analysis, and geo-computation. Remote sensing is a comprehensive technology that deals with the mechanisms of human effects on the natural ecological environment system by observing the earth surface system. Its main areas include sensors and platforms, information processing and interpretation, and natural resource and environmental applications. GIScience and remote sensing provide data and methodological support for resource and environmental science research. They play essential roles in promoting the development of resource and environmental science and other related technologies. This paper provides forecasts of ten future directions for GIScience and eight future directions for remote sensing, which aim to solve issues related to natural resources and the environment.

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1. Introduction

Remote sensing and geographic information science (GIScience) have long been employed to study natural resources and the environment, providing essential data and methodological support. Recently, information and communication technology development has led to a surge of big data and artificial intelligence, which have advanced the research applications of remote sensing and GIScience. With the emergence of big data and geo-computing, geo-referenced data from mobile devices and social media is abundant making up for previous data limitations and providing new research perspectives and frameworks (Zheng et al., 2014; Liu et al., 2015). Furthermore, progressive improvement in computer systems' storage and computing capacities has substantially changed remote sensing and GIScience. New research into panoramic location-based mapping (Zhou et al., 2011), ubiquitous mapping (Guo and Ying, 2017), and pan-spatial information systems (Zhou, 2015) have been proposed. New data models such as 3D/4D grid systems (Holhoş and Roşca, 2018; Sirdeshmukh et al., 2019; Ulmer and Samavati, 2020) have been created, and new information science methods and techniques have been widely adopted. In the field of remote sensing, new imaging modes and technologies, integrated multi-source data, and new intelligent image processing methods have been introduced. In addition, image information processing and interpretation are developing in a more intelligent, dynamic, and quantitative direction (Li, 2003; Tong et al., 2018). Thus, new sources of big data as well as traditional geospatial and remote sensing data will increasingly support the study of natural and socioeconomic phenomena.

The world's population faces challenges from global climate change and mismanagement of natural resources. To overcome these problems, natural resource and environmental science research should provide the ability to understand, simulate and predict these changes. The use of multi-source data and continuous innovations in natural resource and environmental research is an irresistible trend. As a core aspect of "digital China" and "digital earth", remote sensing and GIScience should be employed to help solve the resource and environmental problems faced by China and the world by introducing new methods and techniques to improve management and decision making in natural resources, the environment, natural hazard, public security and transport. This paper clarifies the definitions and frameworks of GIScience and remote sensing and highlights their role in natural resource and environmental science research. We then forecast future directions for GIScience and remote sensing, aimed at solving natural resource and environmental problems.

2. Definitions and frameworks of GIScience and remote sensing

2.1. GIScience

In the context of information systems, GIScience studies the abstract and formal expressions of basic geographic concepts and laws to support resource and environmental science research (Goodchild, 1992a). For this purpose, it is necessary to focus on: 1) modelling resources and environmental elements with different temporal and spatial distributions (geo-modeling) and 2) analyzing and simulating geographic space (geo-analysis). The former solves data structure problems, including spatiotemporal data models and structures (Goodchild, 1992b; Goodchild et al., 2007), geographic information visualization (Andrienko et al., 2003; Koua et al., 2006), spatial cognition (Mark et al., 1999), and knowledge graphs (Janowicz et al., 2012). The latter solves methodological problems, including resources and environmental assessment (Sherrouse et al., 2011), resources and environmental big data analysis (Yao et al., 2017), and intelligent spatiotemporal models (Parker et al., 2003; Li and Liu, 2008). In addition, it is necessary to study 3) geo-computing techniques (geo-computation) to implement and apply the corresponding models and methods under the support of computing technology, including spatiotemporal big data organization and management (Pijanowski et al., 2014), geographic computing systems (Clarke, 2003), environmental simulation (Batty et al., 1999), and decision support (Malczewski, 2006) as shown in Fig. 1.

2.1.1. Geo-modeling

The main objects of geo-modelling include natural and human elements (Goodchild, 1992b). A geographic element has the attributes of spatial location, time, and scale. A geographic element may present different states at different scales, and its representation depends on how it is perceived (Mark 1993). The spatiotemporal conditions (static) or behaviors (dynamic) of geographic elements are geographic phenomena. The regular arrangements of geographic elements in space form geographic patterns (Peuquet, 2001; Yuan, 2001). Geographic processes are the observations of geographic elements, patterns, and systems in the time dimension. A core characteristic of geographic processes is spatial and temporal variability.

2.1.2. Geo-analysis

Geo-analysis is the quantitative study of geospatial phenomena, which processes spatial data into different forms such as spatial measurement, spatial statistics (Anselin and Getis, 1992), clustering (Fotheringham and Zhan, 2010; Pei et al., 2012), network analysis (Xu et al., 2015), and spatiotemporal intelligence (Chapi et al., 2017; Gao, 2020), and extracts potential information and knowledge to support spatial decision-making. Geo-analysis involves the modelling, analysis, simulation, prediction, and optimization of spatial locations, distributions, forms, distances, and relationships. Combined with artificial intelligence, GIScience is no longer merely a tool for spatial simulation. GIScience is expected to break through existing research frameworks by uncovering additional laws in natural resources and the environment by: researching spatiotemporal methods; integrating resources and environmental domain knowledge with artificial intelligence methods; and establishing universal connections of geographic elements, patterns and processes. The basic research areas of geo-analysis include:

(1) Environmental and resource assessments of water, soil, atmosphere and biology through spatial models and analysis to reveal the distribution patterns, interactions, and dynamic evolution. This process should consider different spatial effects, extend classical data mining and analysis methods, and find a compromise between the global universality and local particularity of geographical phenomena.

(2) Geo-analysis establishes spatial analysis model frameworks based on multi-source geographic big data and reveals the coupling relationship and dynamic changes between natural resources and multiple environmental elements with the aid of machine learning, time series analysis, tensor analysis, and other methods.

(3) Geo-analysis explores intelligent spatiotemporal models that integrate the laws of natural resources and the environment by combining black and white boxes, constructing a spatiotemporal intelligent analysis method system for understanding geographic phenomena and modelling geographic processes, and performing geographical tasks such as spatiotemporal pattern extraction, anomaly detection, and unknown variable inference and scenario prediction. This enables overall perception, comprehensive understanding, and intelligent prediction in natural resources and the environment.

2.1.3. Geo-computation

Geo-computation is a research field that uses computer methods to process geographic information and analyze geographic phenomena, involving high-performance computing for geographic information processing and management (Chen et al., 2018), geographic data mining (Mennis and Guo, 2009), geographic process modelling (Brown et al., 2005), and software engineering and computing systems that support processing and analysis. Geo-computing integrates theories and methods

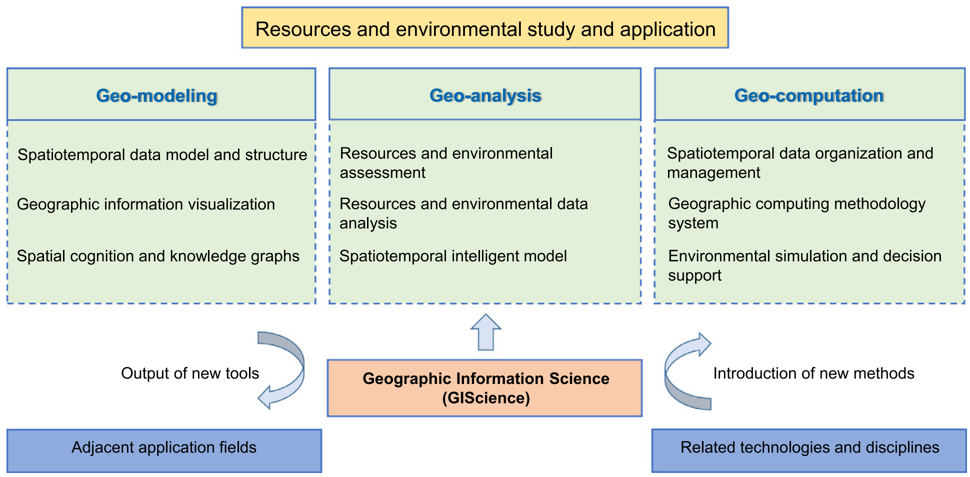

Fig. 1. Definition and framework of GIScience.

in computer science, GIScience, mathematics and statistics and predominantly involves methodologies in GIScience. In the era of big data, natural resource and environmental science research have been afforded new opportunities by the abundance of data on earth observations and human mobility, thus entering the "fourth paradigm" era for data-intensive scientific discovery (Hey et al., 2009; Pei et al., 2020). As the core support for GIScience, geo-computing needs to efficiently manage, analyze and explore large scale spatiotemporal information in this new data environment. In the context of big data, determining and developing effective high-performance computing techniques to form a systematic geographic computing solution is key to overcoming the challenges of data intensiveness and computational intensiveness. There are three main geo-computational research areas:

(1) Organization and management of spatiotemporal data. Geo-computing develops new types of distributed spatial database techniques aimed at difficulties in storing and processing large scale spatiotemporal data. By fusing advanced techniques such as NoSQL (Cattell, 2010) and NewSQL (Pavlo and Aslett, 2016), geo-computing can build big data management models based on new types of distributed computing frameworks to achieve high-efficiency management and access.
(2) Geo-computing methods for multi-modal big data. A high-performance computing system that integrates multi-source spatiotemporal data and micro and macro models is required. Under the support of the new spatiotemporal big data expression frameworks and storage models, this can be realized by integrating advanced computing methods such as cloud computing with high-concurrency spatiotemporal information processing, high-performance spatial analysis and visualization. Moreover, geo-computing supports offline fusion and online assimilation for multi-source spatiotemporal big data and provides strong support for multi-source big data simulation and knowledge-based decision-making.
(3) Applications supported by geo-computing. This research area aims to develop geographical applications with the support of quantitative scientific tools, e.g., spatiotemporal pattern discovery and decision support in natural resources, ecological protection, public health, and disaster prevention and mitigation based on big data calculation and analysis.

2.2. Remote sensing science and technology

Remote sensing science, which involves observation of the earth's surface, examines the macro and micro mechanisms of human behavior on the natural environment related to economic and social development. To meet these aims, it is necessary to focus on research into sensor and platform techniques as well as information processing and interpretation techniques, which are related to the imaging of natural resource and environmental elements. The former deals with data acquisition and system organization of resource and environmental information, whereas the latter solves methodological problems related to the interpretation of resource and environmental information. On this basis, the realization and applications of resource and environmental projects supported by spatial information are further studied as shown in Fig. 2.

2.2.1. Theory and technology related to sensors and platforms for resource and environmental data acquisition

Remote sensing is a technology that measures electromagnetic radiation on the earth's surface through sensors located far from the target. It then transmits, processes, interprets, and analyzes the acquired information in order to monitor the earth's environment system. In the era of the digital earth, all-weather, full-time and full-coverage observation provided by remote sensing is the main method of data acquisition for environmental science research. As a method of spatial data acquisition, remote sensing integrates the theories and methods from geo-information science, aerospace, aviation, physics, computer science, and computational mathematics. It uses methods of remote sensing imaging, i.e., obtaining the geometric and physical attributes of surface elements according to the characteristics of electromagnetic waves, which are reflected or radiated by surface elements then recorded by sensors. The basic remote sensing research areas are described below.

(1) The development of new sensors. From the perspective of space-borne sensors, new advances involve the high-resolution, low light level (i.e., nighttime light) satellite and the microsatellite constellation technology (Eisenberg, 2013), design of space-based real-time imaging observation systems (Xiao et al., 2018), development of space radiometric reference satellite sensor and geosynchronous earth orbit passive/active sensors. From the perspective of aerial-borne sensors, this research area focuses on high precision light-and-small aerial mapping, uncrewed aerial vehicles (UAV) and high-efficiency navigation space synthetic aperture radar (SAR) remote sensing, etc. SAR sensor development is focused on miniaturization, multi-function and multi-mode, e.g., including multi-look polarimetric (Yang et al., 2021), interferometric (Romeiser, 2013), wide-area surveillance.
(2) The mechanism of remote sensors. This area involves the analysis of spectroscopic principles (Ryan and Walker, 2015; Chen et al., 2021), atmospheric dispersion (Zhang et al., 2012), and the optical splitter design of sensors (Shi et al., 2021) based on the principles of active and passive remote sensing imaging. This research area also involves the analysis of sensor imaging geometry to compensate for geometric distortion and to stabilize images

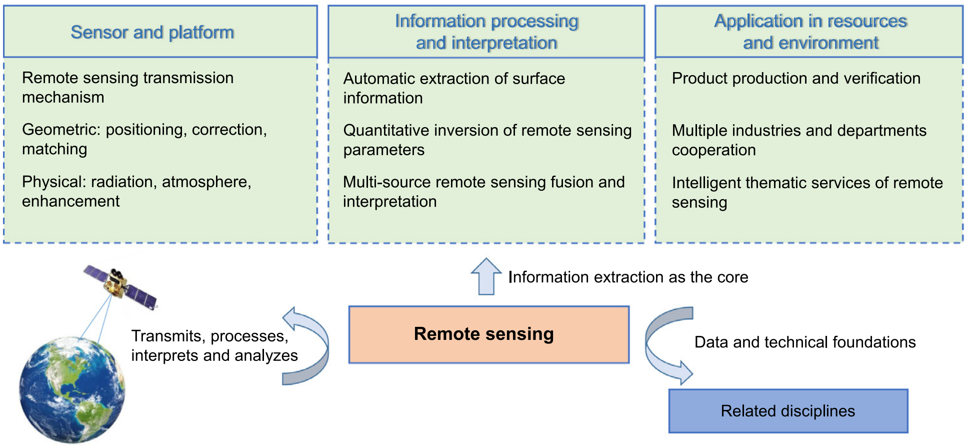

Fig. 2. Definition and framework of remote sensing.

based on the orbital altitude, attitude and time synchronization of satellites and the internal orientation of sensors (Norris and Walker, 2020). Finally, this research area deals with the relationship between payloads and imaging modes, satellite platforms, and ground parameters to improve imaging quality (Ren et al., 2011; Zhang et al., 2021b).

(3) Geometric remote sensing. This research area involves projecting images to a certain object space coordinate system and recovering the geometric position of corresponding objects according to the sensor's external orientation (Toutin, 2004). It involves techniques of space-time datum, data communication and transmission, on-orbit geometric calibration, geometric correction of single-scene images, geometric matching of multi-images, digital elevation/terrain models and orthophoto generation (Wiesel, 1985; Fraser, 1997; Hartmann et al., 2016; Zhang et al., 2019; Abdollahi and Pradhan, 2021).

(4) Physical remote sensing. This research area examines the relationship between the electromagnetic spectrum and information obtained by the sensors based on the imaging mechanism of sensors (Dellwig, 1986). It involves analysis of radiation transfer mechanism models by exploring the relationship between ground radiation signals and earth surface parameters; and atmospheric radiation transfer models by analyzing the influence of the atmosphere on the surface radiation signals received by remote sensors (Tang et al., 2013; Tripathy et al., 2015; Kwok and Ng, 2021).

2.2.2. *Natural resource and environmental information processing and interpretation*

Multi-spectral and multi-period remote sensing images acquired at different locations and altitudes and progressively enhanced remote sensing information can provide comprehensive, systematic, instantaneous or synchronous information of continuous regions that support spatial decision-making in environmental science. The research scope includes remote sensing platforms and platform integration technologies, remote sensors, remote sensing information processing, quantitative remote sensing and remote sensing information engineering. Information processing and interpretation involves the following research areas.

(1) Regarding the requirements of resource and environmental information interpretation, this field analyzes the imaging modes, physical characteristics, geometric characteristics and timeliness of various remote sensors. It combines artificial intelligence in the core techniques of intelligent image information extraction to solve problems such as on-orbit data processing, pattern recognition, automatic interpretation, and computer vision to reveal surface element distribution trends and spatiotemporal patterns.

(2) This field combines models of electromagnetic radiation transmission, dynamic models of resource and environmental changes, statistical models and machine learning algorithms to construct quantitative spatiotemporal evolution models of the earth's surface parameters (physical, chemical and biological) and reveal relationships and processes.

(3) Under the integrated services of comprehensive observation provided by multi-purpose satellites, satellite constellations and multi constellation collaboration, this field involves intelligent complementation and fusion of information with fine and massive multi-platform, multi-layer, multi-sensor, multi-temporal, multispectral, multi-angle and multi-resolution remote sensing data to discover complicated geographic patterns. To make full use of the effectiveness of multi-source satellite systems and meet the needs of diverse applications in natural resources and the environment, this field must solve problems such as spatial data mining and intelligent service engine.

2.2.3. *Applications in the fields of natural resources and the environment*

Through the information transmission mechanism governing the interaction of electromagnetic waves with the five major spheres of the earth (hydrosphere, pedosphere, lithosphere, atmosphere, and biosphere), remote sensing provides services for natural resource and environmental applications and global change at three levels: general investigations, detailed investigations and dynamic monitoring. Research topics include but are not limited to atmospheric remote sensing, marine remote sensing, forestry remote sensing, agricultural remote sensing, environmental remote sensing, surveying and mapping remote sensing, urban remote sensing and national information monitoring. Research includes the following areas.

(1) Basic research on remote sensing applications, remote sensing product production and validation methods, especially the technology of real-time dynamic monitoring data processing for space-based remote sensing. This research focuses on automated, near real-time data validation methods for multiple elements at multiple spatiotemporal scales using multi-platform observations, such as uncrewed aerial vehicles (UAVs) and small sensors.

(2) Examine the integration, planning, connection and coordination between various industries and departments and the joint application of dynamic monitoring data from multi-source remote sensing and ground station networks. Distributed remote sensing software and hardware facilities, data, information, and technologies should be integrated to jointly solve important and common global technical problems in dynamic remote sensing monitoring to improve the level of dynamic earth surface monitoring and the quality information products.

3. Role of GIScience and remote sensing in natural resource and environmental science

3.1. Supporting the research and applications of natural resource and environmental science

Remote sensing and GIScience provide data and methodological support for resource and environmental science research with the help of information technology from the following aspects.

(1) With multi-source spatiotemporal big data, such as remote sensing data, survey sampling data, and station observation data, remote sensing and GIScience can be used to study techniques of data collection, management and distribution, and to solve data quality problems related to data acquisition and management.
(2) Remote sensing and GIS can be used to discover laws, answer questions and optimal decision making by innovating techniques and methods of pattern recognition, process simulation and spatiotemporal prediction.
(3) Considering the high information demands of China, these methods can build analysis and simulation systems by developing hardware and software tools, thereby systemizing scientific achievements in resource and environmental science.
(4) Information technology is a crucial driver for promoting the development of remote sensing and GIScience. By actively introducing advanced technologies in information technology, such as sensor networks, artificial intelligence, and cloud computing, remote sensing and GIScience can connect resource and environmental science research with other disciplines.
(5) Remote sensing is an interdisciplinary research domain emerging from the interconnection of surveying and mapping science, space science, electronic science, earth science, and computer science. It is an important means of obtaining resource and environmental parameters using non-contact sensors.
(6) GIScience investigates the primary theoretical representations and basic methodological framework of resource and environmental science research, focusing on the discipline's core concepts and general tools. Thus, GIScience can achieve more general abstractions of the research objects, which helps maintain the integrity and prevent the "hollowing out" tendency in resource and environmental science.

3.2. Promoting the development of natural resources and environmental science, and related technologies

Remote sensing science has advanced the development of several subject areas and industries including urbanization, information and science, population and health, manufacturing, transportation, public security, national defense, resource supervision, meteorology and oceans. Remote sensing has provided benefits technological changes to crop yield estimation, soil surveys, land use change, disaster monitoring, water resource surveys, water conservation engineering surveys and agro-ecological environment monitoring.

Remote sensing has dramatically increased the amount of primary data and created a solid technological foundation in natural resources and the environment. Over the last several decades Chinese government agencies and university departments related to surveying and mapping, disaster prevention and mitigation, water conservation, land use, geology, meteorology, agriculture, forestry and marine research have been conducting remote sensing research and have accumulated long time series and multi-modal earth observation data.

Remote sensing involves various scientific and technical fields such as aerospace, optoelectronics, physics, earth science, information science, artificial intelligence and cloud computing. Thus, it has boosted innovation and interconnectivity of sensors, electronic information, artificial intelligence, geography, computing science and other domains, enabling the emergence of new disciplines.

GIScience is aimed at meeting the practical needs of regional forestry resources management agencies, mineral exploitation, environmental assessment and natural disaster warning. It has played an important role in establishing high-quality indicators and technical systems for dynamic resource and environmental monitoring. It has also accelerated the development of other related disciplines and technologies. First, GIScience has promoted the efficient collection and management of resource and environmental data. Spatiotemporal data models and spatiotemporal indices, as well as the GIScience abilities of integrative spatiotemporal/transaction data storage and cross-modal computation, have aided the collection efficiency and management quality of multi-source and heterogeneous data, and provided tools and methods for in-depth analysis and application of these data.

Second, GIScience has spurred spatiotemporal data analysis capabilities and applications in natural resource and environmental science research. The research questions in natural resources and geographical environment are usually correlated in time and space. Therefore, to adapt to the regional, dynamic and refined development of these fields, an accurate understanding of geospatial data is required. Intelligent analysis of spatiotemporal big data is an important geospatial data application that provides technical support for spatiotemporal data storage, retrieval and visualization, and collaborative computation, and precise information extraction and visualization (Guo, 2018; Li, 2019).

Third, GIScience has strengthened the interconnectivity of resource and environmental disciplines and related technologies. In recent years, the combination of GIScience and remote sensing with big data, cloud computing and artificial intelligence have experienced substantial progression, contributing to improving theoretical and application development in resource and environmental disciplines.

4. Future developments of GIScience and remote sensing

4.1. General trends of GIScience

The theoretical foundation of GIScience research should be strengthened in the following ways. First, the understanding and expression of core geospatial concepts, such as scale, spatial dependence, and distance, should be enhanced through research in theoretical geography. Second, the formal modelling of geospatial patterns can be developed by introducing relevant mathematical methods, e.g., the mechanisms behind phenomena such as self-organization, nonlinearity, scale-free phenomena and emergence in the complex giant system of geography revealed through the methods of complexity science. Third, the study of spatial cognition provides the cognitive science foundation for geospatial artificial intelligence.

GIScience would not have developed without support from information science. Thus, GIScience should seize the opportunities brought by new technologies such as big data, artificial intelligence, the Internet of things (IoT), blockchain, and high-performance computing to develop new methods and overcome problems of expression, analysis, simulation and prediction in the complex systems of natural resources and the environment.

Most research in the natural resources and the environment focuses on the issue of the "data-method-platform". GIScience needs to contend with issues in the sustainable development of natural resources and the environment. By increasing investment in data, methods and platforms in these fields, research can be conducted on cross-domain collaborative processing, spatiotemporal evolution modelling and intelligent decision making for integrated global observation big data. This will promote the application of geographic information technologies and improve the level of natural resource and environmental research.

4.2. General trends of remote sensing

Remote sensing is an important data source for natural resources and environmental science research, which provides accurate and timely input parameters. The techniques of earth observation, intelligent information processing and multi-source data fusion are developing rapidly and injecting new vitality and power into natural resource and environmental research. This section focuses on "quantitative remote sensing" and "information remote sensing", addressing the strategic development of remote sensing in geographic parameter inversion and information fusion.

4.2.1. Remote sensing parameter inversion

Along with continuous improvements in remote sensing's earth observation capacity and ground-based observation networks, geographic parameter inversion is expected to enhance quantification, precision and clarity. The quantitative extraction of geographic parameters from remote sensing data based on the space-air-ground integrated earth observation networks is an important strategic direction. Specifically, abundant and increasingly domestic space-based observation data are now available. The implementation of high-resolution earth observation programs and rapid development of the civil aerospace industry have enabled China's on-orbit high-resolution satellites to achieve observations over the full spectrum with high-resolution constellations and space-based sensing networks composed of high spatial resolution, hyperspectral, infrared, and radar sensors. In aerial remote sensing, the popularity and commercialization of UAV sensing and the full spectrum coverage have further enhanced the capacity for earth observations. At the same time, ground-based observations have been improved. Ground observation networks for vegetation, soil, water quality, atmosphere, carbon and other elements, combined with aerospace and aerial remote sensing, will guarantee quantified, real-time and accurate remote sensing.

4.2.2. Remote sensing information processing

Remote sensing earth observations are an important data source. The rapidly developing space-air-ground integrated earth observation network will continuously gather massive, multidimensional, and heterogeneous remote sensing data. The distinctive characteristics of big data include not only large volumes but also multi-source and heterogeneous features. However, any single dimension of these data only represent a certain aspect of geographic space and probably includes errors (instrument errors, statistical errors and crowdsourcing errors). Therefore, these multi-source heterogeneous data should be subjected to data fusion, assimilation and integration before they are sued to support geography and as the basis for strategies such as global mapping, the Belt and Road Initiative and sustainable development. Furthermore, to achieve comprehensive remote sensing observations and data integration, it is necessary to establish an integrated space-air-ground observation network and IoT transmission system that supports a big data platform for integrating, analyzing, sharing and serving multi-source observation data for the earth.

4.3. Specific development directions of GIScience and remote sensing in natural resource and environmental science

4.3.1. Geographical information science

We estimate that GIScience developments over the next 15 years will follow ten directions, which can be summarized into three categories: theoretical methods, a new generation of GIS and an integrated data and computing environment.

4.3.1.1. Theoretical methods of GIScience.

(1) Geographic information modelling of natural resources and the environment.

The fundamental research aims of GIScience, which has yet to be completed, involves establishing effective expression models, quantitative evaluation models and scale transformation models of geographic information based on an understanding of the generation, transmission, and transformation mechanisms of information related to the natural and social elements and processes of water, soil, air and biology.

(2) Digital twin representation and interaction of geographic systems.

Current visualizations only take layers for single elements or processes as display units and lack the capacity to display complex spatiotemporal evolution processes. Performing real-time and effective reproduction and interaction of the complex spatiotemporal evolution processes of the environment in the form of a digital twin will overcome the limitations of current visualizations and help users achieve an accurate understanding and exploratory analysis of geographic systems.

(3) Intelligent geographic system simulation and analysis.

Formal expression, integration and reasoning of models and knowledge, especially the implicit empirical modelling knowledge which is crucial for the correct usage of professional models (Qin et al., 2016; Liang et al., 2020), are essential for geographic modelling in complex application scenarios and for performing efficient and accurate simulation and analysis of geographic systems.

4.3.1.2. Developing a new generation of GIS.

(1) GIS architecture and computing service mode.

Build new GIS architecture based on the characteristics of natural resource and environmental science applications, and provide advanced computing service modes that satisfy various functional requirements for a new generation of natural resource and environmental information systems.

(2) Aggregation of big data in natural resources and the environment.

Effective aggregation of various traditional geographic data and new big data related to resources and the environment is necessary when employing "geographic big data" to support all-aspect reproduction and analysis of multiple natural and social elements and processes (e.g., water, soil, air and biology).

(3) Integration and interoperability of knowledge and models in natural resources and the environment.

The integration and interoperability of knowledge and models in various professional fields related to natural resources and the environment make it possible for users to quickly model resources, the environment, disasters, sustainable development and other issues in a flexible and easy-to-use manner (Zhu et al., 2021).

(4) Generation of new resource and environmental information systems.

By integrating the research results of theoretical methods and systems in GIScience, a new generation of natural resource and environmental information systems can emerge. To highlight the different perspectives of this new-generation system, different names such as new generation GIS, full-space geographic information system or virtual environment should be considered.

4.3.1.3. Data-and-computing-integrated major application services in resources and the environment.

(1) Deep-time digital earth.

Deep-time digital earth focuses on the digital reproduction and interaction of the earth system, especially extensions to deep earth and extraterrestrial space in the space dimension and historical geological periods in the time dimension. Constructing a deep-time digital earth platform can provide portal services of geoscience data, models, and knowledge for research and applications in natural resources and the environment.

(2) Virtual experiments coupling natural and human processes.

Virtual geographic experiments provide support for methodological and technical systems in resources and the environment (Lin et al., 2013a,b). Conducting virtual experiments that couple natural and human processes will promote the understanding of various geographic elements, processes and interactions in the geographic system, thereby advancing knowledge discovery.

(3) Decision support for natural resources, the environment, disasters, health and sustainable development.

GIScience should focus on these areas which greatly concern national economies and people's livelihoods. It should also provide real-time system monitoring, modelling and simulation, scenario analysis, early warning and response plan formulation and other decision support.

4.3.2. Remote sensing

The development of remote sensing over the next 15 years can be summarized into three categories: remote sensing mechanisms and models; remote sensing information processing; and quantitative remote sensing and applications.

4.3.2.4. Exploration of remote sensing mechanisms and models in complex scenarios. With the development of new materials, theories and techniques, the electromagnetic spectrum of remote sensing imaging continues to expand, and new sensors continue to emerge. It is necessary to explore new sensor imaging mechanisms and models and develop the theory and methods of radiation transmission between targets and sensors. Traditional remote sensing modelling is mature for relatively homogenous targets and regions. Future research will focus on the 3D radiation transmission modelling for complex targets and regions (such as mountains, cities, and clouds), as well as radiation transmission theories, which are suitable for emerging sensors, and on expanding the exploring domain to deep sea, deep space and deep earth.

4.3.2.5. Intelligent remote sensing information processing. Information remote sensing converts rich and diverse remote sensed data to information and knowledge. This discipline involves the interconnection and integration of remote sensing earth observations and information computing. It has developed new innovations in computer vision, artificial intelligence, cloud computing and big data to increase the depth of remote sensing data mining and to improve the accuracy of remote sensing mapping and related products. Specific directions are discussed below.

(1) Intelligent image interpretation that highlights the original characteristics of remote sensing.

A deep learning neural network is a type of artificial neural network. It attempts to mimic the human brain through a neural network with three or more layers. More hidden layers in deep learning neural networks can help optimize and refine predication accuracy (IBM Could Education, 2020). Deep learning has achieved better accuracy than traditional methods in classic problems of image scene interpretation, stereo vision matching, image classification and target recognition (Huang et al., 2020; Bai et al., 2021; Guan et al., 2021; Ma et al., 2021; Zhang et al., 2021a). However, there is still room for future research in remote sensing related to achieving deep learning based on the characteristics of remote sensing images, such as the interpretability of deep learning models, libraries of large amounts of labeled image samples.

(2) Remote sensing cloud computing that supports multi-source information fusion.

The remote sensing cloud computing model represented by the Google Earth Engine (GEE) has received substantial attention in recent years and achieved great success. Cloud computing spares local users from the complicated pre-processing procedures of image mosaic, correction and positioning. It also removes the need for local storage requirements by cloud storage, enabling true global remote sensing data sharing. The future development of cloud computing involves the spatiotemporal integration of multi-source data, cloud computing functions and capacities, cloud computing resource allocating and deep cloud computing.

(3) Multi-modal remote sensing information mining.

Current aerospace and aerial observations can obtain remote sensing data through UAVs, satellites and airplanes. However, new data sources such as ground observations, field surveys, social media and social statistics are aiding the interpretation of remote sensing data and reducing the uncertainty of remote sensing information extraction. However, some key issues such as correction of multi-source data, fusion methods of multi-source heterogeneous information and fault-tolerant big data analysis require further research.

(4) Remote sensing products and services.

A great deal of remote sensing information and products will be generated from intelligent remote sensing interpretation, cloud computing and big data mining. Thus, quality control and integration of these products are worthy of further study. Future research directions involve making these remote sensing products better serve geo-modelling and geographic analysis, as well as serving national strategies and needs in China such as the "Belt and Road Initiative", "Beautiful China", "Global Mapping" and "Ecological City".

4.3.2.6. Mechanisms and products of high-resolution and large-scale quantitative remote sensing. Quantitative remote sensing retrieves the physical properties of targets based on radiation transmission between sensors and targets. This discipline has been developed from manual visual interpretation and statistical regression to quantitative inversion methods that combine radiation transmission models, machine learning algorithms and multi-source information fusion. Improvement in information extraction accuracy, spatial and temporal resolution, spatiotemporal integrity and timeliness of quantitative remote sensing will provide important data support for geographic element monitoring. Specific research directions include:

(1) Multi-modal quantitative inversion and information fusion.

This direction involves theories and methods for remote sensing from observations to quantitative information. Having undergone long-term development in single-sensor inversion and data fusion, the future development direction of this field is to achieve high-precision, high-temporal-resolution, and multi-element quantitative information extraction through a priori geoscience knowledge obtained by mining big data and multi-modal information from "time-space-spectrum-angle" aspects using advanced machine learning methods.

(2) Quantitative remote sensing validation.

"Objective" validation methods are required for quantitative remote sensing information extraction. Traditional validation methods are mostly based on on-site observations, so they have insufficient representative spatial samples and types of observation elements. With the emergence of advanced observation methods such as UAVs and sensor networks, future directions of quantitative method validation will be based on comprehensive usage of multiple platforms and multi-element observation data and focus on the temporal and spatial scale laws of remote sensing observations and quantitative inversion.

(3) Quantitative remote sensing services for resource and environmental applications.

Continuously expanding applications in the resource and environmental domain brings vitality to quantitative remote sensing through the use of big data, cloud computing, artificial intelligence and other advanced technologies. The deep coupling of quantitative remote sensing models with application models in water, soil, atmosphere, organisms and human activities, will enable new intelligent quantitative information service models oriented at users' demands to be achieved.

5. Conclusion

GIScience studies the abstract and formal expressions of the basic concepts and laws of geography. GIScience research areas include geo-modeling, geo-analysis, and geo-computation. Remote sensing information science deals with the mechanisms of human effects on the natural ecological environment system by observing the earth's surface. The main areas include sensors and platforms, information processing and interpretation, and natural resource and environmental applications. GIScience and remote sensing play important roles in resource and environmental science research by providing data and methodological support, thereby promoting resource and environmental science and other related technologies.

In the new era of knowledge and information advances, the fields of natural resource and environmental science face the dual challenges of data intensiveness and computational intensiveness. Thus, Developments in information science and computer sciences have resulted in many opportunities for GIScience and remote sensing research. To highlight important issues for natural resource and environmental science, we proposed ten directions for GIScience, grouped into three categories (theoretical methods, a new generation of system and integrated data and computing environment), and eight directions for remote sensing, grouped into three categories (remote sensing mechanisms and models, remote sensing information processing and quantitative remote sensing and applications).

Declaration of Competing Interest

The authors declare no conflict of interest.

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References

Abdollahi, A., Pradhan, B., 2021. Integrated technique of segmentation and classification methods with connected components analysis for road extraction from orthophoto images. Expert Syst. Appl. 176, 114908.
Andrienko, N., Andrienko, G., Gatalsky, P., 2003. Exploratory spatio-temporal visualization: An analytical review. J. Visual Lang. Comput. 14 (6), 503–541.
Anselin, L., Getis, A., 1992. Spatial statistical analysis and geographic information systems. Ann. Regional Sci. 26 (1), 19–33.
Bai, X., Wang, X., Liu, X., Liu, Q., Song, J., Sebe, N., Kim, B., 2021. Explainable deep learning for efficient and robust pattern recognition: A survey of recent developments. Pattern Recogn. 120, 108102.
Batty, M., Xie, Y., Sun, Z., 1999. Modeling urban dynamics through GIS-based cellular automata. Comput. Environ. Urban. 23 (3), 205–233.
Brown, D.G., Page, S., Riolo, R., Zellner, M., Rand, W., 2005. Path dependence and the validation of agent-based spatial models of land use. Int. J. Geogr. Inf. Sci. 19 (2), 153–174.
Cattell, R., 2010. Scalable SQL and NoSQL data stores. ACM SIGMOD Rec. 39 (4), 12–27.
Chapi, K., Singh, V.P., Shirzadi, A., Shahabi, H., Bui, D.T., Pham, B.T., Khosravi, K., 2017. A novel hybrid artificial intelligence approach for flood susceptibility assessment. Environ. Model. Softw. 95, 229–245.
Chen, W., Venables, D.S., Sigrist, M.W., 2021. Current trends and future outlook in spectroscopic monitoring of the atmosphere. In: Chen, W., Venables, D.S., Sigrist, M.W. (Eds.), Advances in Spectroscopic Monitoring of the Atmosphere. Elsevier, pp. 1–25.
Chen, Y., Huang, Z., Pei, T., Liu, Y., 2018. HiSpatialCluster: A novel high-performance software tool for clustering massive spatial points. Trans. GIS. 22 (5), 1275–1298.
Clarke, K.C., 2003. Geocomputation's future at the extremes: High-performance computing and nanoclients. Parallel Comput. 29 (10), 1281–1295.
Dellwig, L.F., 1986. Physical fundamentals of remote sensing. Earth Sci. Rev. 25 (3) 254–254.
Eisenberg, A., 2013. Microsatellites: What Big Eyes They Have. New York Times, 2013–8–11.
Fraser, C.S., 1997. Digital camera self-calibration. ISPRS J. Photogramm. 52 (4), 149–159.
Fotheringham, A.S., Zhan, F.B., 2010. A Comparison of three exploratory methods for cluster detection in spatial point patterns. Geogr. Anal. 28 (3), 200–218.
Gao, S., 2020. A review of recent research and reflections on geospatial artificial intelligence. Geomatics Inf. Sci. Wuhan Univ. 45 (12), 1865–1874.
Goodchild, M.F., 1992a. Geographical information science. Int. J. Geogr. Inf. Sci. 6 (1), 31–45.
Goodchild, M.F., 1992b. Geographical data modeling. Comput. Geosci. 18 (4), 401–408.
Goodchild, M.F., Yuan, M., Cova, T.J., 2007. Towards a general theory of geographic representation in GIS. Int. J. Geogr. Inf. Sci. 21 (3), 239–260.
Guan, J., Yang, X., Ding, L., Cheng, X., Lee, V.C.S., Jin, C., 2021. Automated pixel-level pavement distress detection based on stereo vision and deep learning. Autom. Constr. 129, 103788.
Guo, H., 2018. Scientific big data – A footstone of national strategy for big data. Bull. CAS. 33 (8), 768–773.
Guo, R., Ying, S., 2017. The rejuvenation of cartography in ICT era. Acta Geodaetica et Cartographica Sinica 46 (10), 1274–1293 (in Chinese).
Hartmann, W., Havlena, M., Schindler, K., 2016. Recent developments in large-scale tie–point matching. ISPRS J. Photogramm. 115, 47–62.
Holhoş, A., Roşca, D., 2018. Uniform refinable 3D grids of regular convex polyhedrons and balls. Acta Math. Hungarica. 156 (1), 182–193.
Huang, T., Zhang, Q., Liu, J., Hou, R., Wang, X., Li, Y., 2020. Adversarial attacks on deep--learning-based SAR image target recognition. J. Netw. Comput. Appl. 162, 102632.
Janowicz, K., Scheider, S., Pehle, T., Hart, G., 2012. Geospatial semantics and linked spatiotemporal data–Past, present, and future. Semant. Web. 3 (4), 321–332.
Koua, E.L., Maceachren, A., Kraak, M.J., 2006. Evaluating the usability of visualization methods in an exploratory geovisualization environment. Int. J. Geogr. Inf. Sci. 20 (4), 425–448.
Kwok, Y.T., Ng, E.Y.Y., 2021. Trends, topics, and lessons learnt from real case studies using mesoscale atmospheric models for urban climate applications in 2000–2019. Urban Clim. 36, 100785.
Li, D., 2003. Towards the development of remote sensing and GIS in the 21st century. Geomatics Inf. Sci. Wuhan Univ. 28 (2), 127–131 (in Chinese).
Li, D., 2019. The intelligent processing and service of spatiotemporal big data. J. Geo-Inf. Sci. 21 (12), 1825–1831.
Liang, P., Qin, C.Z., Zhu, A.X., Hou, Z.W., Fan, N.Q., Wang, Y.J., 2020. A case-based method of selecting covariates for digital soil mapping. J. Integr. Agr. 19 (8), 2127–2136.
Lin, H., Chen, M., Lu, G., 2013a. Virtual geographic environment: A workspace for computer-aided geographic experiments. Ann. Assoc. Am. Geogr. 103 (3), 465–482.
Lin, H., Chen, M., Lu, G., Zhu, Q., Gong, J., You, X., Wen, Y., Xu, B., Hu, M., 2013b. Virtual Geographic Environments (VGEs): A new generation of geographic analysis tool. Earth Sci. Rev. 126, 74–84.
Liu, Y., Liu, X., Gao, S., Gong, L., Kang, C., Zhi, Y., Chi, G., Shi, L., 2015. Social sensing: A new approach to understanding our socioeconomic environments. Ann. Am. Assoc. Geogr. 105 (3), 512–530.
Li, X., Liu, X., 2008. Embedding sustainable development strategies in agent-based models for use as a planning tool. Int. J. Geogr. Inf. Sci. 22 (1), 21–45.
Ma, A., Wan, Y., Zhong, Y., Wang, J., Zhang, L., 2021. SceneNet: Remote sensing scene classification deep learning network using multi-objective neural evolution architecture search. ISPRS J. Photogramm. 172, 171–188.
Malczewski, J., 2006. GIS-based multicriteria decision analysis: A survey of the literature. Int. J. Geogr. Inf. Sci. 20 (7), 703–726.
Mark, D.M., 1993. Toward a theoretical framework for geographic entity types. In: Frank, A.U., Campari, I. (Eds.), Spatial Information Theory: A Theoretical Basis for GIS, Lecture Notes in Computer Sciences. Springer-Verlag, Berlin, pp. 270–283.
Mark, D.M., Freksa, C., Hirtle, S.C., Lloyd, R., Tversky, B., 1999. Cognitive models of geographical space. Int. J. Geogr. Inf. Sci. 13 (8), 747–774.
Mennis, J., Guo, D., 2009. Spatial data mining and geographic knowledge discovery-An introduction. Comput. Environ. Urban. 33 (6), 403–408.
Norris, J.R., Walker, J.J., 2020. Solar and sensor geometry, not vegetation response, drive satellite NDVI phenology in widespread ecosystems of the western United States. Remote Sens. Environ. 249, 112013.
Parker, D.C., Manson, S.M., Janssen, M.A., Hoffmann, M.J., Deadman, P., 2003. Multi-agent systems for the simulation of land-use and land-cover change: A review. Ann. Assoc. Am. Geogr. 93 (2), 314–337.
Pavlo, A., Aslett, M., 2016. What's really new with NewSQL? ACM SIGMOD Rec. 45 (2), 45–55.
Pei, T., Gao, J., Ma, T., Zhou, C., 2012. Multi-scale decomposition of point process data. GeoInformatica 16 (4), 625–652.
Pei, T., Song, C., Guo, S., Shu, H., Liu, Y., Du, Y., Ma, T., Zhou, C., 2020. Big geodata mining: Objective, connotations and research issues. J. Geogr. Sci. 30 (2), 251–266.
Peuquet, D.J., 2001. Making space for time: Issues in space-time data representation. Geoinformatica 5, 11–32.
Pijanowski, B.C., Tayyebi, A., Doucette, J., Pekin, B.K., Braun, D., Plourde, J., 2014. A big data urban growth simulation at a national scale: Configuring the GIS and neural network based Land Transformation Model to run in a High Performance Computing (HPC) environment. Environ. Model. Softw. 51, 250–268.
Qin, C.Z., Wu, X.W., Jiang, J.C., Zhu, A.X., 2016. Case-based knowledge formalization and reasoning method for digital terrain analysis – Application to extracting drainage networks. Hydrol. Earth Syst. Sci. 20, 3379–3392.
Ren, H., Yan, G., Chen, L., Li, Z., 2011. Angular effect of MODIS emissivity products and its application to the split-window algorithm. ISPRS J. Photogramm. 66 (4), 498–507.

Romeiser, R., 2013. Ocean applications of interferometric SAR. In: Njoku, E.G. (Ed.), Encyclopedia of Remote Sensing. Springer, New York.
Ryan, N.J., Walker, K.A., 2015. The effect of spectroscopic parameter inaccuracies on ground-based millimeter wave remote sensing of the atmosphere. J. Quant. Spectrosc. Ra. 161, 50–59.
Sherrouse, B.C., Clement, J.M., Semmens, D.J., 2011. A GIS application for assessing, mapping, and quantifying the social values of ecosystem services. Appl. Geog. 31 (2), 748–760.
Shi, P., Yang, A., Meng, F., Chen, J., Zhang, Y., Xie, Z., Du, L, Yuan, X., 2021. Optical near-field measurement for spin-orbit interaction of light. Prog. Quant. Electron. 78, 100341.
Sirdeshmukh, N., Verbree, E., Oosterom, P.V., Psomadaki, S., Kodde, M., 2019. Utilizing a discrete global grid system for handling point clouds with varying locations, times, and levels of detail. Cartographica 54 (1), 4–15.
Tang, R., Li, Z.L., Sun, X., 2013. Temporal upscaling of instantaneous evapotranspiration: An intercomparison of four methods using eddy covariance measurements and MODIS data. Remote Sens. Environ. 138, 102–118.
Tong, Q., Meng, Q., Yang, H., 2018. The history and future of remote sensing technology. City Disaster Reduct. (6) 2–11 (in Chinese).
Hey, T., Tansley, S., Tolle, K., 2009. The Fourth Paradigm: Data-intensive Scientific Discovery. Microsoft Press, Redmond, Washington.
Toutin, T., 2004. Geometric processing of remote sensing images: Models, algorithms and methods. Int. J. Remote Sens. 25 (10), 1893–1924.
Tripathy, M., Raman, M., Chauhan, P., 2015. Estimation of photosynthetically available radiation (PAR) from OCEANSAT-I OCM using a simple atmospheric radiative transfer model. Adv. Space Res. 56 (7), 1441–1452.
Ulmer, B., Samavati, F., 2020. Toward volume preserving spheroid degenerated-octree grid. Geoinformatica 24, 505–529.
Wiesel, J., 1985. Digital image processing for orthophoto generation. Photogrammetria 40 (2), 69–76.
Xiao, A., Wang, Z., Wang, L., Ren, Y., 2018. Super-resolution for "Jilin-1" satellite video imagery via a convolutional network. Sensors 18, 1194.
Xu, J., Chen, Y., Xu, M., 2015. Data mining and application of spatial networks. Commun. China Comput. Federation. 11 (11), 40–47 (in Chinese).
Yang, R., Dai, B., Tan, L., Liu, X., Yang, Z., Li, H., 2021. Classification of polarimetric SAR images. In: Yang, R., Dai, B., Tan, L., Liu, X., Yang, Z., Li, H. (Eds.), Polarimetric Microwave Imaging. Springer, pp. 445–483.
Yao, Y., Li, X., Liu, X., Liu, P., Liang, Z., Zhang, J., Mai, K., 2017. Sensing spatial distribution of urban land use by integrating points-of-interest and Google Word2Vec model. Int. J. Geogr. Inf. Sci. 31 (4), 825–848.
Yuan, M., 2001. Representing complex geographic phenomena in GIS. Am. Cartographer. 28 (2), 83–96.
Zhang, E., Liu, L., Huang, L., Ng, K.S., 2021a. An automated, generalized, deep-learning-based method for delineating the calving fronts of Greenland glaciers from multi-sensor remote sensing imagery. Remote Sens. Environ. 254, 112265.
Zhang, Q., Pang, Z., Hu, W., Li, J., Liu, Y., Liu, Y., Yu, F., Zhang, C., Xu, M., 2021b. Performance degradation mechanism of the light-activated room temperature NO2 gas sensor based on Ag-ZnO nanoparticles. App. Surf. Sci. 541, 148418.
Zhang, X., Jiang, T., Li, X., Zhang, X., 2012. Research on application of PcModtran in design of satelliteborne optical remotes sensor. Phys. Procedia 25, 822–828.
Z. Zhang, Y., Fattahi, H., Amelung, F., 2019. Small baseline InSAR time series analysis: Unwrapping error correction and noise reduction. Comput. Geosci. 133, 104331.
Zheng, Y., Capra, L., Wolfson, O., Yang, H., 2014. Urban computing: Concepts, methodologies, and applications. ACM Trans. Intell. Syst. Technol. 5 (3), 38.
Zhou, C., 2015. Prospects on pan-spatial information system. Prog. Geogr. 34 (2), 129–131.
Zhou, C., Zhu, X., Wang, M., Shi, C., Ou, Y., 2011. Panoramic location-based map. Prog. Geogr. 30 (11), 1331–1335.
Zhu, A.X., Zhao, F.H., Liang, P., Qin, C.Z., 2021. Next generation of GIS: Must be easy. Ann. GIS. 27 (1), 71–86.
IBM Could Education. 2020. Deep learning. https://www.ibm.com/cloud/learn/deep–learning (accessed 24 July, 2021).