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RESEARCH

Trends and applications of google earth engine in remote sensing and earth science research: a bibliometric analysis using scopus database

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Abstract
Since its official establishment in 2010, Google Earth Engine (GEE) has developed rapidly and has played a significant role in the global remote sensing community. A bibliometric analysis was conducted on 1995 peer-reviewed articles related to GEE, indexed in the Scopus database up to December 2022 to investigate its trends and main applications. Our main findings are as follows: (1) The number of GEE-related articles has increased rapidly, with nearly 85% of them published in the last three years; (2) The top three domains where GEE has been extensively applied are earth and planetary sciences, environmental science, and agricultural and biological sciences. The majority of GEE-related articles were authored by scholars from China and the US, accounting for 58% of the total, with US scholars having the largest impact on the community, contributing to over 50% of the total citations; (3) Remote Sensing published the highest number of articles (26.82%), whereas Remote Sensing of Environment received the highest number of citations (30.40%); (4) The applications of GEE covered a broad range of topics, with a focus on land applications, water resource applications, climate change, and crop mapping; (5) Landsat imagery were the most popular and widely used dataset; and (6) Random forest, decision trees, support vector machines were the most commonly used machine learning algorithms in GEE. Although having a few limitations, this type of analysis should be conducted regularly to observe the development of this field on a regular basis, as the number of publications related to GEE is expected to continue to increase strongly in the coming years.

Keywords Cloud computing platform · Google Earth Engine (GEE) · Scientometrics · Science mapping

Introduction

Over the last decade, the number of earth observation satellites has increased significantly, providing a massive amount of remote sensing observations and data. Thanks to the free data policy of some of the biggest space agencies, such as the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA), all observations acquired by the most important satellites (i.e., Landsat series, MODIS, Sentinel-1, -2, and -3, etc.) have been provided regularly and freely to the community, for scientific and educational purposes (Pham-Duc et al. 2017). For storing, processing and analyzing this huge amount of remote sensing data acquired by these satellites, cloud computing platforms, equipped with supercomputers, are efficient tools (Chi et al. 2016).

Nowadays, Amazon Web Services (AWS), Microsoft Azure, and Google Earth Engine (GEE) cloud platforms are the three largest competitors, providing the ability to process global geospatial satellite data. AWS, released in 2006 by Amazon, has its Earth on AWS services (https://aws.amazon.com/earth/), which supports planetary-scale applications

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with open geospatial data from several satellites, such as Sentinel-1 and -2, Landsat-8, China-Brazil Earth Resources Satellite, and National Oceanographic and Atmospheric Administration Advanced (NOAA) (Tamiminia et al. 2020). Azure (https://azure.microsoft.com/en-us/), released in 2010 by Microsoft, provides machine learning and Artificial Intelligence (AI) services for addressing the four main directions of environmental challenges, including climate, agriculture, biodiversity, and water (Mahdavi et al. 2018). Azure has only provided Landsat and Sentinel-2 products for North America since 2013, and MODIS imagery since 2000. As private companies, both AWS and Azure are pay-as-you-go platforms where users pay based on the hours they use their services.

In contrast, GEE (https://earthengine.google.com/), established in 2010 by Google, is a free cloud computing platform that enables users to conduct geospatial analysis on a global scale using Google's infrastructure (Gorelick et al. 2017). Compared to its competitors, GEE offers a wider range of satellite imagery types (i.e., Landsat series, MODIS, Sentinel-1, -2, -3, and -5P, NOAA, Advanced Land Observing Satellite (ALOS), etc.), along with climate, weather and geophysical datasets. It also provides ready-to-use products such as the Enhanced Vegetation Index (EVI) and the Normalized Difference Vegetation Index (NDVI) (Kumar and Mutanga 2018). There are several ways to interact with GEE, using the Code Editor, the Explorer or the Client libraries. The Code Editor is a web-based IDE (Integrated Development Environment) for the Earth Engine JavaScript Application Programming Interface (API), designed for developing and running complex geospatial workflows quickly and easily. The Explorer is a simple web interface to the Earth Engine API, designed for exploring and visualizing data in the public data catalog and running simple analyses. The Client libraries contain wrapper functions written in JavaScript or Python, that allow users to build custom applications. GEE, thanks to its free access (which is extremely important for users in developing countries) and numerous advantages, is currently the most popular cloud computing platform for the remote sensing community (Zhao et al. 2021). It has emerged as a powerful tool for analyzing earth and environmental processes, with numerous studies in the field of earth sciences and environment utilizing this platform. GEE's ability to process vast amounts of satellite imagery and geospatial data has enabled researchers to study land cover changes, monitor ecosystem health, disasters, diseases, food security, and assess the impacts of climate change on natural resources and human communities (Gorelick et al. 2017). GEE has been widely applied in various fields related to earth science and environmental science (Tamiminia et al. 2020). It has found applications in land studies (Huang et al. 2017; Zurqani et al. 2018; Raj and Sharma 2022), hydrology (Pekel et al. 2016; Pham-Duc et al. 2022; Nghia et al. 2022; Orieschnig et al. 2022), agriculture (Lobell et al. 2015; Dong et al. 2016; Xiong et al. 2017; Bhavana et al. 2023), climate change (Workie and Debella 2018), forestry (Chen et al. 2017; Bullock et al. 2020), urbanization (Liu et al. 2018), wetlands monitoring (Waleed et al. 2023), and disaster analysis (Meilianda et al. 2019; DeVries et al. 2020). Moreover, GEE has facilitated the development of new methods for mapping and monitoring land use/cover, carbon emissions, and other environmental indicators, providing critical insights for sustainable development planning and policy-making.

There are only a few review articles about GEE available in the literature. Gorelick et al. (2017) published the first review article providing an overview of the system architecture of GEE, its data catalog and data distribution models, as well as the main applications, challenges and future work of GEE. Kumar and Mutanga (2018) analyzed 300 peer-reviewed articles published between 2011 and 2017 to investigate the usage patterns, trends and potential of GEE, and whether users from developing countries were making use of GEE. Tamiminia et al. (2020) analyzed 349 peer-reviewed articles published between 2010 and 2019 to provide the first meta-analysis and systematic review of GEE, focusing on several features, including data, sensor type, study area, spatial resolution, application, strategy, and analytical methods. At the same time, Amani et al. (2020) analyzed 450 peer-reviewed articles published between 2010 and 2020 to conduct a review on different aspects of GEE, including its datasets, functions, advantages/limitations, and its applications. Zhao et al. (2021) investigated the trends and applications of both GEE and Google Earth (GE) by analyzing 565 and 1334 peer-reviewed articles related to GEE and GE, respectively. The most recent systematic review was performed on 343 articles published in high-impact scientific journals, selected from the Scopus and Google Scholar databases from 2020 to 2022 in which they particularly focused on publications during the COVID-19 outbreak (Pérez-Cutillas et al. 2023). These review articles were quite comprehensive; however, there were still limitations. Three papers used only articles published in the Google Scholar and Web of Science (WoS) databases (Kumar and Mutanga 2018; Tamiminia et al. 2020; Zhao et al. 2021). As a result, the number of publications used for their analysis was quite limited. The Scopus database should also be used, as it is the largest bibliographic database with wider coverage and detailed indexing (Eito-Brun 2018). Analyses in these articles have been done using Excel, ArcGIS, EndNote and CiteSpace, but not the most popular bibliographic software (i.e., Biblioshiny and VOSviewer). As a consequence, some analyses could not be done due to technical limitations of these tools. In addition, this emerging research field is developing quickly; therefore, it is important and necessary to conduct regularly this type of bibliometric analysis in order to closely observe its development.

The main objective of this paper is to provide a comprehensive overview of the development of the GEE's visibility using the most updated bibliographic data derived from the Scopus database. The focus is on analyzing the international collaboration networks among scholars and countries, as well as the co-occurrence network of related keywords. Bibliometric analysis, first introduced by Pritchard 1969, was utilized as it is one of the most effective approaches for this purpose. Bibliometric analysis has previously been applied to investigate the development and international collaboration networks of applications of remote sensing in various academic fields (Zhuang et al. 2013; Hu et al. 2017; Duan et al. 2020; Yu et al. 2023). It has also been used to examine trends in utilizing data from different earth observation satellites, such as Cryosat (Eito-Brun 2018), Landsat (Hemati et al. 2021), and Sentinel-1 (Pham-Duc and Nguyen 2022).

To achieve our objectives, it is necessary to answer these following questions:

1. What has been the growth rate of the number of GEE related articles?
2. How were the international collaboration networks between countries and scholars?
3. Which scientific journals and research institutions published the most articles?
4. Which sponsors provided the most research funding?
5. Which articles have had the most significant impact on the community based on the number of citations?
6. In which research directions has GEE been most frequently untilized, based on keyword analysis?

Materials and methods

Bibliometric analysis was utilized to analyze the trends of using GEE globally, following the guidelines presented in (Pham-Duc et al. 2020; Pham-Duc and Nguyen 2022). The search query (Box 1) was used to retrieve relevant original and review articles from the Scopus database (https://www.scopus.com/, accessed on February 15, 2023). Compared to other databases, the Scopus has the widest coverage, which is why it was selected as the main search engine for this study. We searched all original articles written in English containing the keyword *"Google Earth Engine"* in their titles, abstracts and keywords (Tamiminia et al. 2020; Zhao et al. 2021). Then, the authors manually screened the titles and abstracts of the publication collection to eliminate irrelevant papers. Metadata of the final output collection was exported to bibliography (.BIB) and comma-separated values (.CSV) files for post-processing using VOSviewer (van Eck and Waltman 2010) and Biblioshiny software (Aria and Cuccurullo 2017). VOSviewer is a free Java tool for analyzing, constructing and visualizing bibliometric networks. This tool is highly effective for displaying the graphical representation of large bibliometric maps in an easy-to-interpret manner. Biblioshiny is an open-source program in the R environment that provides different tools for executing a comprehensive science mapping analysis of scientific literature. Each software has its advantages and limitations. Using both software allows researchers to draw a comprehensive overview of the development of a research direction based on the growth of the number of articles and citations, the collaboration networks of countries, institutions and scholars, as well as the co-occurrence network of keywords (Pham-Duc et al. 2021). Both software work with bibliographic metadata files generated from Scopus and WoS databases, and they have been updated regularly.

Box 1 The search query string used in this study

TITLE-ABS-KEY ("Google Earth Engine") AND PUBYEAR < 2023 AND (LIMIT-TO (DOCTYPE,"ar")) AND (LIMIT-TO (LANGUAGE,"English"))

Results

General statistical information

Primary statistical information of the publication collection is shown in Table 1. Although GEE was officially launched in 2010, the first papers discussing its use were published in 2015. Since then, until the end of 2022, a total of 1995 articles have been published in 346 different journals indexed in the Scopus database. The publication collection has received a total of 35,692 citations as of the time of this study. There were 6,086 different authors, with 10,685 author appearances, whereas there were only 27 single-authors who published 34 single-authored papers (1.7% of the publication

Table 1 Main statistical information of the publication collection of 1995 original and review articles related to GEE, published in the Scopus database during the 2015–2022 period

Description	
Original articles & review papers	1995
Citations	35,692
Sources	346
Period	2015—2022
Authors	6,086
Author appearances	10,685
Authors of single-author documents	27
Authors of multi-author documents	6,054
Single-authored documents	34
Average citations per document	17.93
Authors per document	3.05
Co-authors per document	5.35
Documents per author	0.33

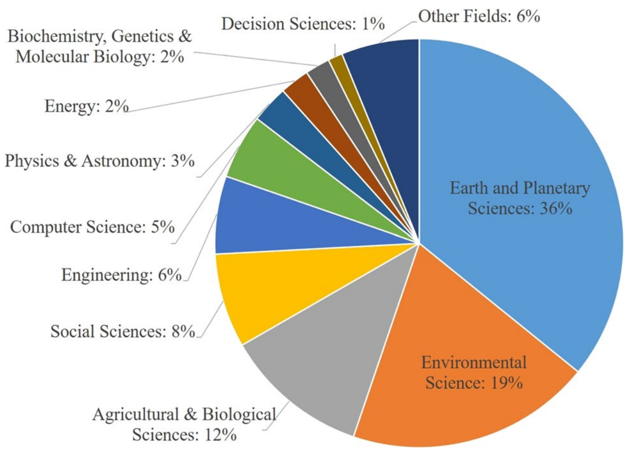

Fig. 1 Research disciplines in which GEE was applied

collection). On average, each paper received nearly 18 citations and has 5.35 co-authors. Additionally, each scholar had an average of 0.33 documents.

After being published, each article was automatically assigned to one (or several) Scopus Category of research. Figure 1 shows the top ten disciplines in which GEE has been predominantly applied. The primary areas include earth and planetary sciences (36%), environmental science (19%), and agricultural and biological sciences (12%). These three research areas alone contribute to almost 67% of the publication collection. Other research areas where GEE was used include social sciences (8%), engineering (6%), computer science (5%), physics and astronomy (3%), energy (2%), biochemistry, genetics and molecular biology (2%), and decision sciences (1%).

Figure 2 (left) indicates the annual numbers of publications and their cumulative number from 2015 to 2022. The number of articles published per year increased significantly, starting with 6 and 12 publications in 2015 and 2016, respectively. The annual publication count then rose to 32 in 2017 and 82 in 2018. Specifically, 2019 marked the first year when the annual number of publications exceeded 100 articles. The recent three years accounted for 85% of the publication collection, with 359 papers in 2020, 519 papers in 2021, and 818 papers in 2022, respectively. Figure 2 (right) indicates the number of citations received by all articles published in each year at the time of this study. Six articles published in 2015 received a total of 772 citations, while twelve articles published in 2016 received a total of 1250 citations. Thirty-two articles published in 2017 received 7565 citations, with the paper by Gorelick et al. (2017) alone accounting for 4785 citations. Excluding this article, the number of citations increased gradually during the 2015–2020 period as the number of papers increased sustainably. Articles published in 2021 and 2022 received fewer citations, as expected, since these articles require more time to have a greater impact on other scholars and the research community.

Collaboration between countries

Our retrieved results showed that the publication collection was contributed by scholars from 122 countries. Table 2 shows the top ten most productive countries based on the

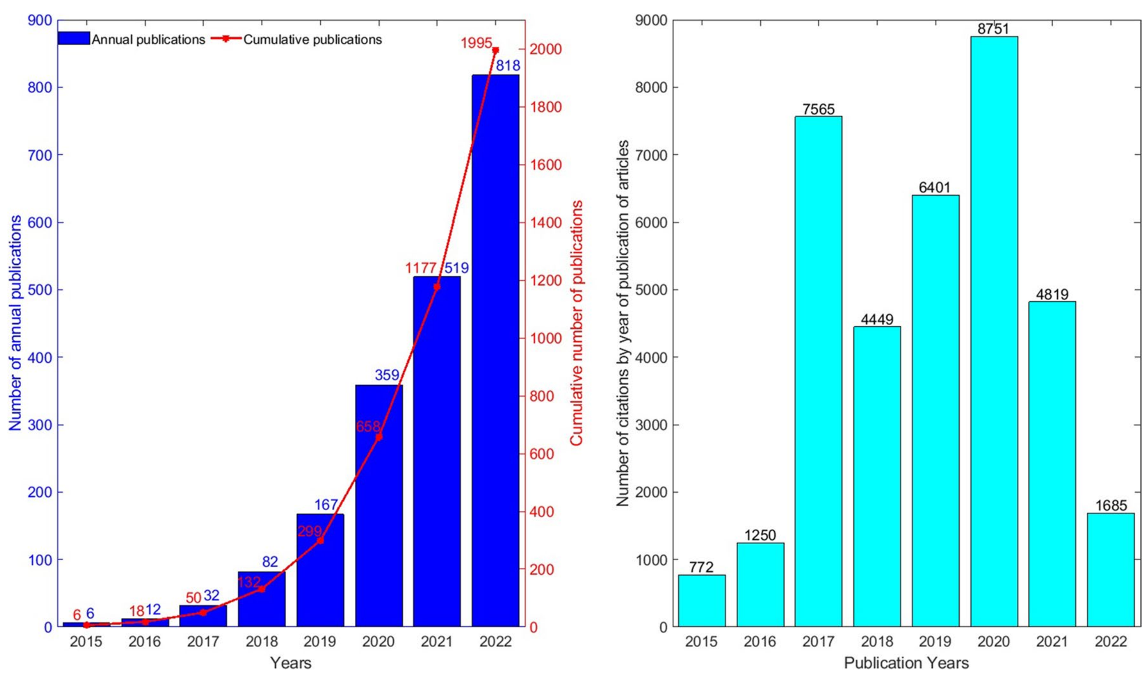

Fig. 2 Annual numbers of publications and its cumulative number (left), and number of citations by year of publication of articles (right) during the 2015–2022 period

Table 2 Top ten most productive countries based on the number of articles and citations

Order	Country	Total articles	%	Total Citations	%
1	China	760	38.10	11,480 (#2)	32.16
2	USA	530	26.56	18,970 (#1)	53.15
3	India	147	7.37	1875 (#6)	5.25
4	Canada	107	5.36	2290 (#4)	6.41
5	Germany	107	5.36	1829 (#7)	5.12
6	UK	101	5.06	1902 (#5)	5.32
7	Brazil	98	4.91	1421 (#9)	3.98
8	Australia	96	4.81	2421 (#3)	6.78
9	Italy	95	4.76	1778 (#8)	4.98
10	Iran	78	3.90	969 (#10)	2.71

number of articles and citations. China ($n = 760$) and the USA ($n = 530$) published the highest number of articles, accounting for 38.10% and 26.56% of the collection, respectively. India ranked third with 147 articles, representing 7.37% of the collection. With more than 100 papers from each country, Canada and Germany ($n = 107$), and the UK ($n = 101$) were in the successive three positions. Brazil ($n = 98$), Australia ($n = 96$), and Italy ($n = 95$) occupied the seventh to ninth positions, respectively. Iran completed the top ten with 78 articles.

Based on the number of citations, the USA ($n = 18{,}970$) and China ($n = 11{,}480$) swapped positions. These two countries received significantly more citations than others, constituting 53.15% and 32.16% of the total citations, respectively. Australia ($n = 2421$) was in the third position, followed by Canada ($n = 2290$) and the UK ($n = 1902$). Although India ranked third based on the number of articles, it moved to the sixth position in terms of citations ($n = 1875$), followed by Germany ($n = 1829$), Italy ($n = 1778$) and Brazil ($n = 1421$). Iran was the only country in the top ten to receive fewer than one thousand citations ($n = 969$). The top ten countries published a total of 1661 articles, which accounted for 83.26% of the total publications, and received 33,127 citations, representing 92.81% of the total citations.

A visualization of the international collaboration network between 59 countries which published at least six articles is shown in Fig. 3. Each node represents a country. The size of nodes is proportional to the number of publications, whereas

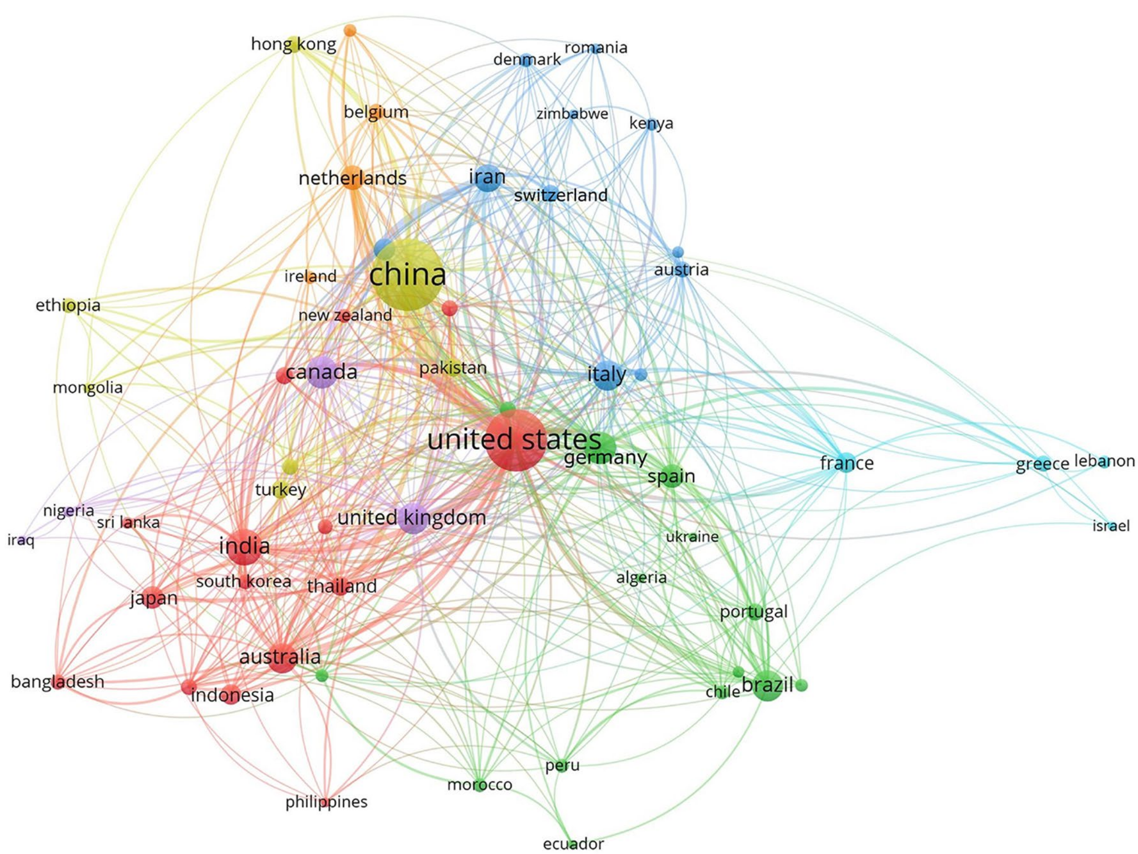

Fig. 3 International collaborations between 59 countries published at least six articles. Each node represents a country. The size of nodes is proportional to the number of publications, whereas the thickness of lines between nodes is proportional to the strength of collaboration between partner countries

the thickness of lines between nodes is proportional to the strength of collaboration between partner countries. As the most important contributors, the USA and China appear at the center of the collaboration network. Seven different clusters (coded by different colors) are formed based on the collaboration between these partner countries. The first cluster (yellow) is formed mainly based on the collaboration between China and Hong Kong, Pakistan, Turkey, Mongolia, Ethiopia and Egypt. The USA is in the center of the second cluster (red), including Australia, India, Japan, Thailand, Indonesia, and Bangladesh. The third cluster (green) is formed mainly based on the collaboration between European countries (Germany, Spain, and Portugal) and South American countries (Brazil, Chile, Peru, and Ecuador). The fourth cluster (blue) shows the collaboration between other European countries (Italy, Austria, Switzerland, and Denmark) and African countries (Kenya, Zimbabwe and South Africa) and Iran. For the three remaining clusters, each has four countries, including the UK, Canada, Nigeria and Iraq (the violet cluster), France Greece, Israel, and Lebanon (the cyan cluster), and the Netherlands, Belgium, Norway and Ireland (the orange cluster).

Collaboration between scholars

The international collaboration network among 155 scholars who published at least seven publications related to GEE is shown in Fig. 4. Each node represents a scholar, and the size of nodes is proportional to the number of publications and citations. The thickness of lines between nodes indicates the strength of collaboration between scholars, based on the number of articles on which they were co-authors. Scholars belonging to the same research teams are grouped into the same clusters, which are coded by different colors. It is clear that Chinese scholars have made a great contribution to the development of this field, as the center of the collaboration network is formed mainly by Chinese scholars (Fig. 4-top). Seven different clusters can be identified among the Chinese scholars, while three other clusters (blue, green and red) are formed mainly by scholars from the USA and Canada. The blue cluster revolves around Thau D. who works at Google Headquarters in the USA. The green cluster is formed around some scholars such as Clinton N., Poortinga A., and Saah D. The red cluster is centered around Amani M. and Brisco B. who work in Canada. Although Chinese scholars represent a significant proportion of scientists working on GEE, American scholars have the greatest influence on the community based on the number of citations (Fig. 4-bottom). Thau D. from Google (the blue cluster) is the one who received the highest number of citations. A few Chinese scholars have garnered a large number of citations, such as Dong J., Xiao X., and Qin Y. in the cyan cluster; Gong P., Wang J., Zhu Z., Yang J., and Li X. in the yellow cluster. Clinton N. in the green cluster, who works at Google Headquarters, also has a great influence in this field.

A list of the top ten scholars based on the number of articles and citations and their h-index are shown in Tables 3 and 4, respectively. Amani M. and Dong J. were in the first two positions with 23 and 20 articles, respectively. There were three scholars who published more than 15 articles (Xiao X., Gong P., and Clinton N.), whereas the five remaining scholars published between 11 and 14 articles. The top ten most productive scholars published a total of 107 articles, which accounted for 5.36% of the total publications, and received a total of 4894 citations, which accounted for 13.71% of the total citations. Among the top ten, four scholars are from China, two from the USA, two from Canada, one from Iran, and one from Hong Kong. As shown in Table 4, Thau D. ($n = 5898$; 16.52%) and Gorelick N. ($n = 5226$; 14.64%) were in the first two positions with outstanding numbers of citations compared to other scholars. Note that Gorelick N. did not appear in Fig. 4 because the network only displays scholars who published more than six articles. There were five scholars who received more than one thousand citations, including Xiao X. ($n = 1504$), Dong J. ($n = 1351$), Gong P. ($n = 1318$), Clinton N. ($n = 1266$), and Qin Y. ($n = 1146$). The last three positions belong to scholars working in the USA, including Lobell D. B. ($n = 988$), Congalton R. G. and Yaday K. ($n = 969$). The top ten scholars in Table 4 published only 80 articles, which accounted for 4% of the total publications, but received a total of 10,540 citations, which accounted for 29.53% of the total citations. Among the top ten, seven scholars are from the USA, whereas Switzerland, China and Hong Kong have only one each.

Journal published the most articles

Scientific articles related to GEE have been published in a growing number of journals. As shown in Table 1, the collection of 1995 articles was published in 346 different journals. Figure 5 indicates the contribution of top journals based on the number of articles, whereas Table 5 shows detailed information about the top ten journals that published the most articles related to GEE. *Remote Sensing* ranked first with an impressive number of articles ($n = 535$), which accounted for 26.82% of the total publications, and received 9256 citations, which accounted for 25.93% of the total citations. *Remote Sensing of Environment* was in the second position with 106 articles (5.31%) and 10,852 citations (30.40%). They were the only two journals that published more than 100 articles related to GEE. In the third position was the *International Journal of Applied Earth Observations and Geoinformation* with 60 articles (3.00%) and 1183 citations (3.31%). Other journals in Table 5 are *Sustainability* ($n = 44$), *ISPRS Journal of Photogrammetry and Remote Sensing* ($n = 43$), *Land* ($n = 43$), *Remote Sensing Applications: Society and Environment*

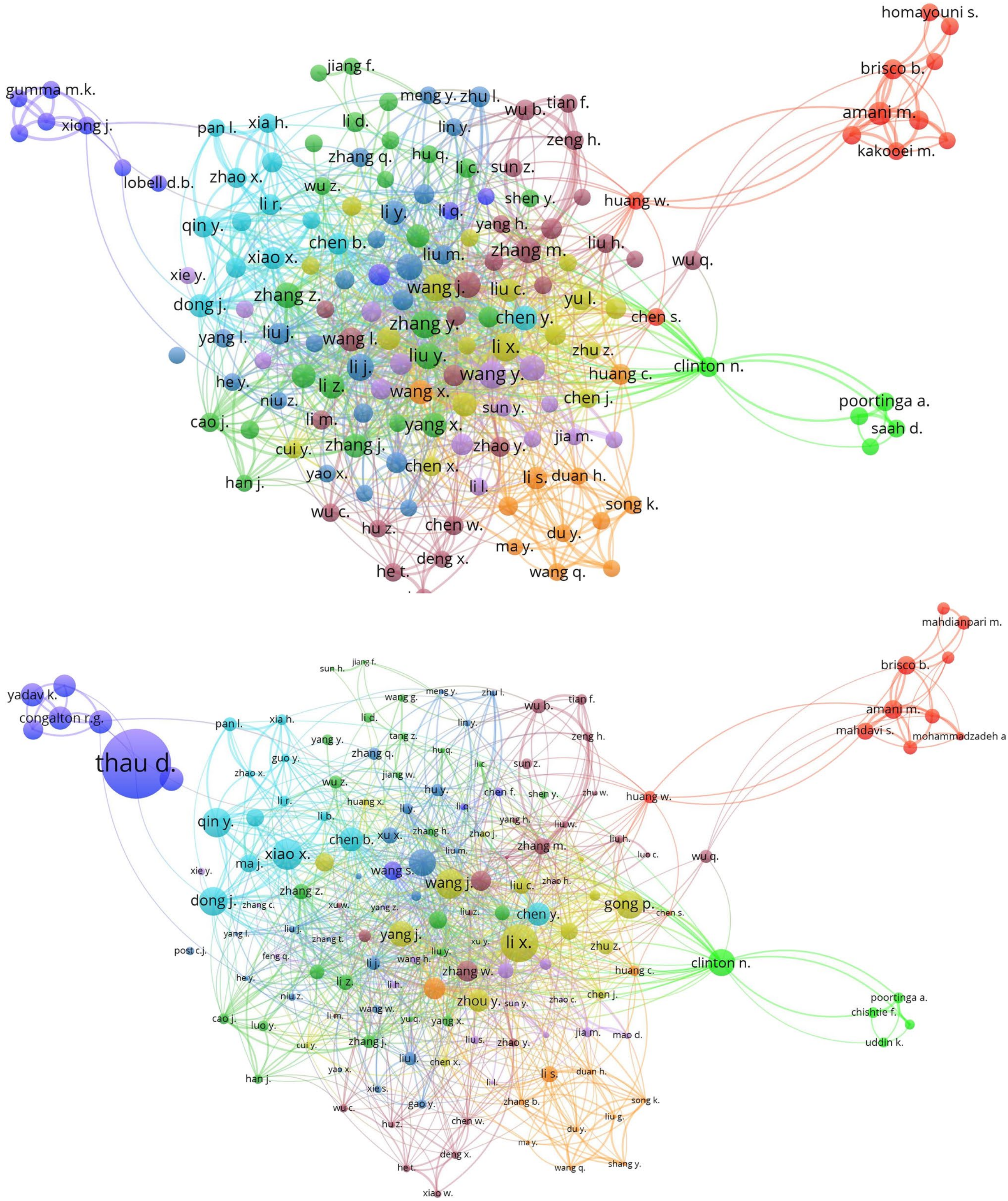

Fig. 4 International collaboration network of 155 scholars who published at least seven articles related to GEE, based on the number of publications (top) and the number of citations (bottom). Each node represents a scholar. The size of nodes is proportional to the number of publications and citations, whereas the thickness of lines between nodes is proportional to the strength of collaboration between scholars

Table 3 Top ten scholars based on the number of articles

Order	Author	Institution/ Country	No. of articles	No. of citations	h-index
1	Amani M	Wood Environment & Infrastructure Solutions/ Canada	23	670	11
2	Dong J.*	Chinese Academy of Sciences/ China	20	1351	13
3	Xiao X.*	University of Oklahoma/ USA	17	1504	15
4	Gong P.*	The University of Hong Kong/ Hong Kong	16	1318	10
5	Clinton N.*	Google Headquarters/ USA	15	1266	13
6	Wu B	Chinese Academy of Sciences/ China	14	447	11
7	Brisco B	Canada Center for Mapping and Earth Observation/ Canada	13	660	11
8	Ghorbanian A	Toosi University of Technology/ Iran	12	439	7
9	Huang H	Sun Yat-sen University/ China	12	523	6
10	Ma J	Fudan University/ China	11	1159	13

* Scholars also appear in Table 4

($n=42$), *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* ($n=41$)*, Science of the Total Environment* ($n=38$)*,* and *ISPRS International Journal of Geo-Information (*$n=30$*).* The top ten journals published 982 articles, which accounted for 49.22% of the total, and received 25,500 citations, which accounted for 71.45% of the total. Among the top ten journals, five belong to Elsevier, four to the Multidisciplinary Digital Publishing Institute (MDPI), and one to the Institute of Electrical and Electronics Engineers (IEEE) publishing house. Except for *Land* which was classified into the second quartile (Q2) category, all nine other journals were classified into the first quartile (Q1) category, according to information retrieved from the *SCImago Journals & Country Rank*. Except for *Remote Sensing Applications: Society and Environment* which belongs to the WoS Emerging Sources Citation Index (ESCI) collection (meaning that this journal does not have a journal impact factor), nine other journals belong to both the Scopus database and the WoS - Science Citation Index Expanded (SCIE) collection.

The annual numbers of articles published by the top ten journals are shown in Fig. 6. *Remote Sensing* published its first three articles related to GEE in 2016, then the contribution of this journal increased quickly every year, and more and more accounted for a larger proportion in recent years. During the 2017–2022 period, each year *Remote Sensing* alone published more articles than the number of articles from nine other journals combined. The number of articles published in *Remote Sensing of Environment* increased gradually during the 2015–2020 period; however, over the last two years, less articles related to GEE have been published in this journal. Although having much less publications compared to *Remote Sensing* and *Remote Sensing of Environment*, in the recent five years (2018–2022), all eight other journals in the top ten published regularly papers related to GEE.

Institutions published the most articles

A list of the top ten institutions that published the most articles related to GEE is presented in Table 6. One notable finding is that public institutions and universities from China take eight out of ten positions, while the remaining two positions belong to the United State Geological Survey (USGS)

Table 4 Top ten scholars based on the number of citations

Order	Author	Institution/ Country	No. of citations	No. of articles	h-index
1	Thau D	Google Headquarters/ USA	5898	7	6
2	Gorelick N	Google Switzerland/ Switzerland	5226	6	6
3	Xiao X.*	University of Oklahoma/ USA	1504	17	15
4	Dong J.*	Chinese Academy of Sciences/ China	1351	20	13
5	Gong P.*	The University of Hong Kong/ Hong Kong	1318	16	10
6	Clinton N.*	Google Headquarters/ USA	1266	15	13
7	Qin Y	University of Oklahoma/ USA	1146	9	7
8	Lobell D. B	Stanford University/ USA	988	7	7
9	Congalton R. G	University of New Hampshire/ USA	969	8	7
10	Yadav K	University of New Hampshire/ USA	969	8	7

* Scholars also appear in Table 3

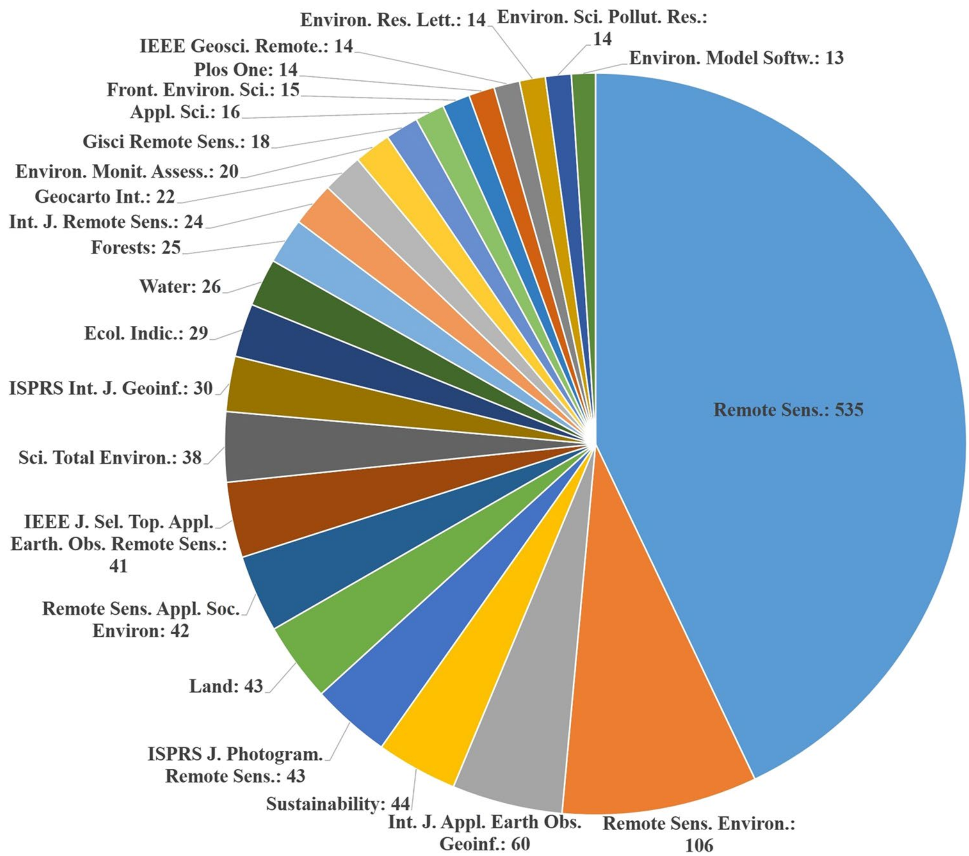

Fig. 5 Journals in which articles related to GEE were published

and Google Headquarters in the USA. Among the Chinese institutions, the Chinese Academy of Sciences (CAS) ranked first with an outstanding number of publications ($n = 331$), which accounted for 16.60% of the total publications. With 109 articles, the Ministry of Education of China (MEC) was in the second position, followed by State Key Laboratory of Remote Sensing Science (SLRSS) ($n = 57$) and Wuhan University ($n = 46$). Other institutions listed in Table 6 published between 30 and 40 articles at the time of this study. Despite being ranked tenth, Google Headquarters received the highest number of citations ($n = 8019$), which accounted for 22.46% of the total citations. This outcome is expected since Google's publications played a significant role in shaping the research direction using GEE. The top ten institutions published a total of 566 articles (28.37%) and received a total of 16,946 citations (47.48%).

Most important funding sponsors

Moving on to funding sponsors, Table 7 presents a list of the top ten sponsors for projects utilizing GEE. These funding sponsors are mostly from China (3), the USA (3), Brazil (2), and European (2). The National Natural Science Foundation of China secured the first position with 450 articles, followed by National Key Research and Development Program of China ($n = 172$), Chinese Academy of Sciences ($n = 165$), and NASA ($n = 147$). The number of studies funded by other sponsors listed in Table 7 is significantly lower compared to the top four sponsors. The top ten funding sponsors have been acknowledged in 899 articles with 14,655 citations, which accounted for 45.06% and 41.06% of the total publications and citations, respectively.

Most cited articles

A list of the top ten most cited articles related to GEE is shown in Table 8, along with detailed information about the publishing journals, the first author's affiliation address, and the research area and main dataset used in each article. *Remote Sensing of Environment* (Q1; IF = 13.850) published six over ten articles, whereas *ISPRS Journal of Photogrammetry and Remote Sensing* (Q1; IF = 11.774) and *Remote Sensing* (Q1; IF = 5.349) each journal published two articles in the top ten. Except for the article by Gorelick et al. (2017), conducted by Google, which received 4785 citations (13.40% of the total), nine other papers received 2906 citations (8.14% of the total). Thau D. from Google Headquarters is the only scholar being co-author of four over ten most cited articles. Gorelick et al. (2017) provided an overview of the system architecture of GEE, its data catalog and data

Table 5 The top ten journals published the most articles related to GEE

Order	Journals	Publishing house	No. of articles	%	No. of citations	%	h-index	Quartile*	Impact factor 2021
1	Remote Sensing *(RS)*	MDPI	535	26.82	9256 (#2)	25.93	48	Q1	5.349
2	Remote Sensing of Environment *(RSE)*	Elsevier	106	5.31	10,852 (#1)	30.40	43	Q1	13.850
3	International Journal of Applied Earth Observation and Geoinformation	Elsevier	60	3.00	1183 (#4)	3.31	17	Q1	7.672
4	Sustainability	MDPI	44	2.20	208 (#9)	0.58	8	Q1	3.889
5	ISPRS Journal of Photogrammetry and Remote Sensing	Elsevier	43	2.15	1948 (#3)	5.45	22	Q1	11.774
6	Land	MDPI	43	2.15	174 (#10)	0.48	10	Q2	3.905
7	Remote Sensing Applications: Society and Environment	Elsevier	42	2.10	427 (#7)	1.20	10	Q1	N/A
8	IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing	IEEE	41	2.05	662 (#5)	1.85	11	Q1	4.715
9	Science of the Total Environment	Elsevier	38	1.90	509 (#6)	1.42	12	Q1	10.753
10	ISPRS International Journal of Geo-Information	MDPI	30	1.50	281 (#8)	0.78	10	Q1	3.099

* According to the SCImago Journal & Country Rank (https://www.scimagojr.com/), accessed on 15 February, 2023

distribution models, as well as the main applications, challenges and future work of GEE. Dong et al. (2016) used Landsat-8 images in GEE for rice paddy mapping in northeastern Asia. The authors reported a high accuracy with the producer and user accuracy of 73% and 92%, respectively, compared to validation data of very high resolution images and field photos. Liu et al. (2018) used Landsat images for the 1990–2021 period to construct global urban land maps with a five-year interval. Gong et al. (2020) used GEE to construct annual maps of global artificial impervious areas from 1985 to 2018 using Landsat images. Huang et al. (2017) used Landsat NDVI time-series data processed in GEE to detect major land cover dynamics in Beijing, and mapping land cover types in 2015. The last most cited article in Table 8 is a review of the usage, trends and potential of GEE (Kumar and Mutanga 2018). These articles are core publications in different successful applications of GEE, and therefore, have great impact on the community.

Keywords analysis

A word cloud of the 154 most frequent keywords plus those that appeared at least 20 times in the publication collection is shown in Fig. 7. To enhance the visibility of important keywords, the terms "Google Earth Engine" and "Remote Sensing" were eliminated, as they appeared in nearly every article in the collection. In Fig. 7, keywords with a higher frequency are displayed in a larger font size, with larger text indicating greater importance. It is evident that "*Landsat*" is the most important keyword, as it appears at the center of the word clouds with the largest font size. This aligns with expectations, as Landsat observations, available since the 1970s, are the most suitable dataset, and have been used broadly for environmental monitoring. Other notable research directions utilizing GEE include the use of NDVI for vegetation monitoring and forestry, as well as mapping land use/land cover changes. Figure 7

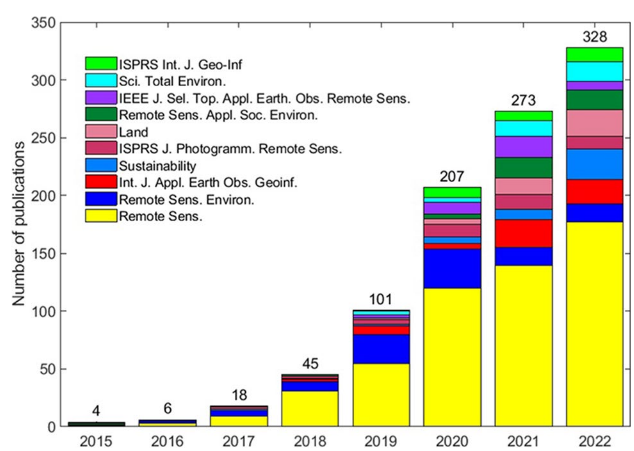

Fig. 6 Annual number of articles published by the top ten journals in Table 5

Table 6 The top ten institutions published most articles related to GEE

Order	Institutions	Country	No. of articles	%	No. of citations	%
1	Chinese Academy of Sciences (CAS)	China	331	16.60	5656	15.85
2	Ministry of Education of China (MEC)	China	109	5.46	3021	8.46
3	State Key Laboratory of Remote Sensing Science (SLRSS)	China	57	2.85	1571	4.40
4	Wuhan University	China	56	2.80	1128	3.16
5	Beijing Normal University	China	41	2.05	905	2.54
6	Sun Yat-Sen University	China	40	2.00	1496	4.20
7	Tsinghua University	China	39	1.95	1854	5.20
8	United States Geological Survey (USGS)	USA	36	1.80	1885	5.28
9	Henan University	China	33	1.65	535	1.50
10	Google Headquarters	USA	32	1.60	8019	22.46

reveals additional insights, such as: (1) Spatial–temporal analysis and time series analysis have been applied widely in GEE for climate change studies; (2) In terms of algorithms used in GEE, random forest, decision trees and machine learning are the most popular ones; (3) After Landsat, Sentinel-1, MODIS, and Sentinel-2 observations have been used the most in GEE; and (4) China and the United States are the most popular study areas, as these are the only two keywords related to geography that appear in the word clouds.

A word cloud is useful in identifying the most important research topics; however, it does not explicitly demonstrate the connection between different keywords. In Fig. 8, a deeper analysis using the co-occurrence network tool in VOSviewer was conducted to illustrate these connections. In this visualization, each node represents a keyword, with the size of nodes proportional to the frequency appearance. Four clusters can be identified by grouping related keywords with strong connections which were determined by the frequency they appeared together in publications. The first cluster (green) encompasses articles focusing on using GEE for land applications such as studying the ecosystems, forestry, mapping LULC changes, deforestation, urbanization and environmental monitoring and protection. Landsat data has been extensively employed for these applications. The second cluster (red) includes articles focusing on the use of GEE for climate change studies, vegetation monitoring using NDVI, hydrology applications such as drought/flood mapping and lake/river monitoring, as well as mapping atmospheric and land surface temperature. MODIS observations are suitable for these applications. The third cluster (blue) includes articles focusing on machine learning algorithms (mainly decision trees, random forests and support vector machines), used in GEE for image analysis and image classification and accuracy assessment. Sentinel-1 and Sentinel-2 observations are popular for these applications. The last cluster (yellow) includes additional important keywords, such as crop mapping, vegetation mapping, and food supply.

Discussions

Although being established in 2010, GEE has only recently become popular, especially over the last three years, when nearly 85% of articles related to GEE have been published

Table 7 The top ten funding sponsors for projects using GEE

Order	Institutions	Country	No. of articles
1	National Natural Science Foundation of China (NFSC)	China	450
2	National Key Research and Development Program of China (NKPs)	China	172
3	Chinese Academy of Sciences (CAS)	China	165
4	National Aeronautics and Space Administration (NASA)	USA	147
5	United States Geological Survey (USGS)	USA	98
6	National Science Foundation (NSF)	USA	70
7	European Space Agency (ESA)	EU	58
8	National Council for Scientific and Technological Development (CNPq)	Brazil	50
9	Coordination for the Improvement of Higher Education Personnel (CAPES)	Brazil	38
10	Horizon 2020 Framework Programme	EU	35

Table 8 The top ten articles received the most number of citations

Title	Authors	Source	First author's Institution/ Country	Research area/ Dataset used	Year	No. of citations	Yearly average citations
Google Earth Engine: Planetary-scale geospatial analysis for everyone (Gorelick et al. 2017)	Noel Gorelick; Matt Hancher; Mike Dixon; Simon Ilyushchenko; David Thau; Rebecca Moore	Remote Sensing of Environment (Q1; IF = 13.850)	Google/ Switzerland	Introduction to GEE	2017	4785	684
Mapping paddy rice planting area in northeastern Asia with Landsat 8 images, phenology-based algorithm and Google Earth Engine (Dong et al. 2016)	Jinwei Dong; Xiangming Xiao; Michael A. Menarguez; Geli Zhang; Yuanwei Qin; David Thau; Chandrashekhar Biradar; Berrien Moore	Remote Sensing of Environment	University of Oklahoma/ USA	Rice mapping/ Landsat-8	2016	462	58
High-resolution multi-temporal mapping of global urban land using Landsat images based on the Google Earth Engine Platform (Liu et al. 2018)	Xiaoping Liu; Guohua Hu; Yimin Chen; Xia Li; Xiaocong Xu; Shaoying Li; Fengsong Pei; Shaojian Wang	Remote Sensing of Environment	Sun Yat-sen University/ China	Urban land mapping/ Landsat series	2018	377	63
Annual maps of global artificial impervious area (GAIA) between 1985 and 2018 (Gong et al. 2020)	Gong et al. 2020	Remote Sensing of Environment	Tsinghua University/ China	Mapping artificial impervious area/ Landsat series	2020	362	90
Reconstructing Three Decades of Land Use and Land Cover Changes in Brazilian Biomes with Landsat Archive and Earth Engine (Souza et al. 2020)	Souza et al. 2020	Remote Sensing (Q1; IF = 5.349)	Imazon/ Brazil	Mapping land use/land cover (LULC) changes/ Landsat series	2020	324	81
A scalable satellite-based crop yield mapper (Lobell et al. 2015)	David B. Lobell; David Thau; Christopher Seifert; Eric Engle; Bertis Little	Remote Sensing of Environment	Stanford University/ USA	Crop yield mapping/ Landsat series	2015	305	34
Automated cropland mapping of continental Africa using Google Earth Engine cloud computing (Xiong et al. 2017)	Jun Xiong; Prasad S. Thenkabail; Murali K. Gumma; Pardhasaradhi Teluguntla; Justin Poehnelt; Russell G. Congalton; Kamini Yadav; David Thau	ISPRS Journal of Photogrammetry and Remote Sensing (Q1; IF = 11.774)	USGS/ USA	Cropland mapping/ MODIS	2017	298	43
Google Earth Engine Applications Since Inception: Usage, Trends, and Potential (Kumar and Mutanga 2018)	Lalit Kumar & Onisimo Mutanga	Remote Sensing	University of New England/ Australia	Investigation the usage patterns of GEE	2018	280	47

Table 8 (continued)

Title	Authors	Source	First author's Institution/ Country	Research area/ Dataset used	Year	No. of citations	Yearly average citations
Mapping major land cover dynamics in Beijing using all Landsat images in Google Earth Engine (Huang et al. 2017)	Huang et al. 2017	Remote Sensing of Environment	Chinese Academy of Sciences/ China	Land cover dynamics mapping/ Landsat series	2017	258	37
A mangrove forest map of China in 2015: Analysis of time series Landsat 7/8 and Sentinel-1A imagery in Google Earth Engine cloud computing platform (Chen et al. 2017)	Chen et al. 2017	ISPRS Journal of Photogrammetry and Remote Sensing	Ministry of Agriculture/ China	Mapping mangrove forest/ Landsat-7/-8 & Sentinel-1	2017	240	34

(Fig. 2). However, GEE has been used the most in the remote sensing community, mainly focusing on earth and planetary sciences and environmental science, while applications of GEE in other scientific domains are still very minimal (Fig. 1). In addition, GEE has been used the most by scholars from developed countries, as the top ten countries accounted for nearly 84% of the total publications and 93% of the total citations (Table 2). With a stable internet connection, GEE provides equal accessibility of its facilities and its data to everybody; therefore, more efforts should be done to introduce this computing platform to scholars in developing countries, especially African and Asian countries (Kumar and Mutanga 2018). Organizing free hands-on training webinars on applications of GEE in different fields, such as land applications, is one of the most effective ways to attract no or little-experienced users to start using GEE for their research (ARSET 2021).

The dominance of the USA and China is clearly seen, as these two countries accounted for about 58% of the total publications and 72.5% of the total citations, respectively (Table 2 and Fig. 3). This dominance can also be observed in other fields of satellite remote sensing, such as using data from the Sentinel-1 satellite mission for Earth monitoring (Pham-Duc and Nguyen 2022). However, these numbers are still less than the contribution of the USA and China to the global scientific research, as these two nations together dominated almost two-thirds of the world research publication output (Toney and Flagg 2021). One of the reasons for this domination is that these two nations provided various funding sources to public institutions for conducting scientific projects (Tables 6 and 7). The international collaboration network (Fig. 4) suggests that China is using a lot of resources to invest in this emerging research field by creating different research groups in several universities and public institutions; however, American scholars, especially the ones working at Google, formed this research field, and had the biggest influence on the community.

Similar to what has been observed in previous articles about the journal selection of other fields related to satellite remote sensing (Hemati et al. 2021; Pham-Duc and Nguyen 2022), a large proportion of GEE-related articles were published in *Remote Sensing* and *Remote Sensing of Environment* (Fig. 5). The number of articles published in *Remote Sensing* was five times higher than in *Remote Sensing of Environment*; however, *Remote Sensing* only accounted for a quarter of the total citations, whereas *Remote Sensing of Environment* accounted for nearly one-third of that. In addition, *Remote Sensing of Environment* published six of the top ten most cited papers, whereas *Remote Sensing* only published two of them (Table 8). *Remote Sensing* is very popular with Chinese scholars, as about 49.8% of its publications during the 2013–2023 period was from China (https://app.scilit.net/sources/737); however, articles published in

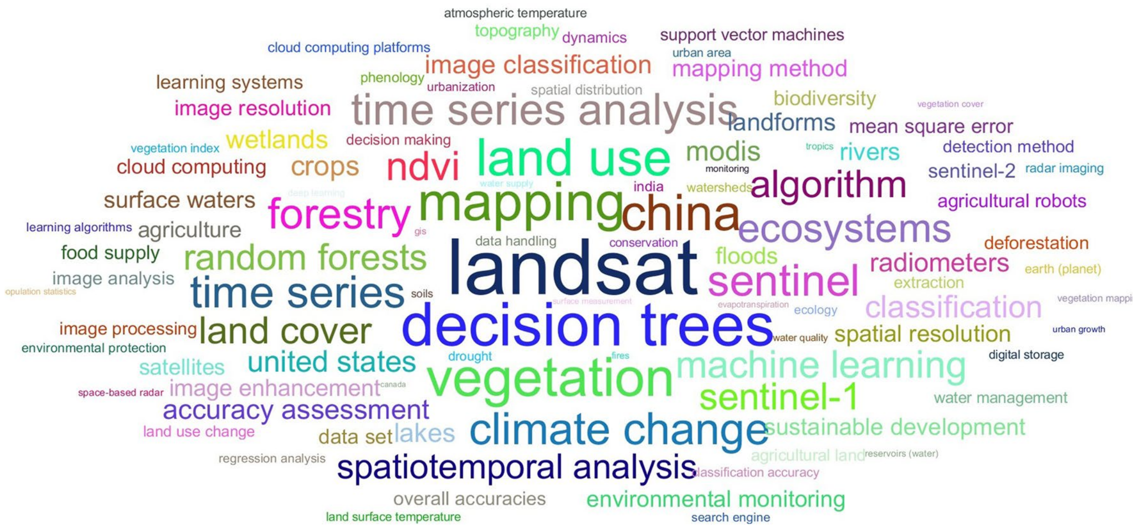

Fig. 7 Word clouds of 154 most frequent keywords plus which appeared at least 20 times

Remote Sensing of Environment have the most impact on the community.

In addition to remote sensing, the research areas of earth and planetary sciences, environmental science, and agricultural sciences have been the primary domains where GEE has been applied. By analyzing the content of articles shown in Table 8, it is clear that these most cited articles focused on the use of GEE for land applications, such as urban mapping (Liu et al. 2018) and LULC mapping (Huang et al. 2017; Souza et al. 2020), and for agriculture applications, such as rice mapping (Dong et al. 2016), and crop mapping (Lobell et al. 2015; Xiong et al. 2017). In addition, imagery from the Landsat satellites is the most popular dataset being used in GEE. This finding agrees with results reported in previous articles (Tamiminia et al. 2020). The use of observations acquired from other satellites (i.e., MODIS, Sentinel-1, and -2) in GEE is still limited; therefore, future work should focus more on taking advantage of GEE for data processing and analysis, especially with Sentinel-1 and -2 observations (Pham-Duc et al. 2022).

The keyword analysis provides insights into the dominant application areas of GEE, methodological advancements in image analysis, and collaborative networks within the research community. It showcases the wide range of applications of GEE in environmental monitoring, land management, and ecosystem analysis, as well as the integration of advanced techniques like machine learning and deep learning for image classification and analysis. The dominant application areas of GEE can be identified by examining frequently co-occurring keywords. Keywords such as "remote sensing", "satellite imagery", "land cover", and "vegetation" indicate the utilization of GEE in analyzing and monitoring Earth's surface using satellite data (Figs. 7 and 8). The presence of keywords in Fig. 8 such as "machine learning", "deep learning", and "image classification" suggests that researchers have been exploring advanced techniques for image analysis and classification using GEE. This indicates the integration of machine learning algorithms and deep learning architectures to extract information from satellite imagery at different scales. The keyword analysis can also provide insights into collaborative networks within the GEE research community. Examining co-occurring keywords can reveal connections between different research groups and thematic areas. For instance, if keywords "deforestation", "forest monitoring", and "biodiversity" frequently appear together, it suggests collaborations between researchers focusing on environmental monitoring and conservation using GEE. Similarly, co-occurring keywords like "urbanization", "land use change", and "GIS" (Geographic Information Systems) indicate collaborations between researchers studying urban dynamics and land use patterns with GEE. As an emerging field, this information is useful to new users of GEE for defining potential research topics, collaboration networks, or identifying research gaps to be conducted in the future.

Conclusions

In this study, a publication collection of 1995 peer-reviewed articles related to GEE published in the Scopus database during the 2015–2022 period has been analyzed using bibliometric analysis. GEE has played an important role in the fields of earth and planetary sciences, and environmental sciences. GEE can be applied in a variety of remote sensing applications, from regional to global scales. Based on our analysis, several conclusions can be drawn: (1) The number of articles

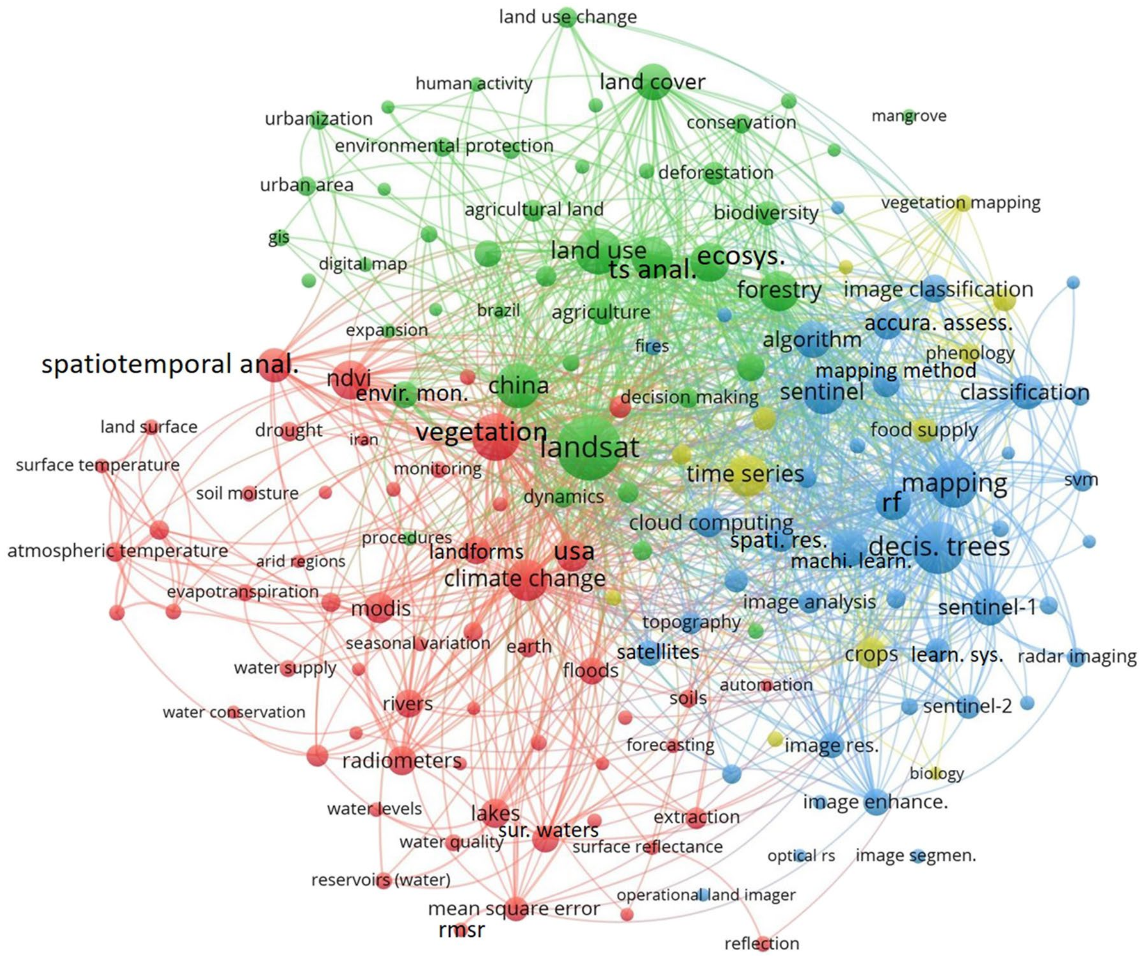

Fig. 8 The co-occurrence network of the 154 most frequent keyword plus in Fig. 7. Each node represents a keyword, and thickness between nodes represents the strength of the relationship between keywords, determined by the frequency they appeared together in publications

related to GEE increases fast every year, with a much higher increasing rate since 2019. This increasing trend is expected to continue in the future when GEE becomes more and more popular, not only for the remote sensing community, but also for scientists working in other fields; (2) Scholars from the USA and China have the largest influence on the development and visibility of GEE. Chinese scholars dominated the number of publications; however, US scholars had a much bigger impact on the community as they accounted for more than 50% of the total citations. In addition, publications by the research team in Google played a very important role in this field; (3) *Remote Sensing* and *Remote Sensing of Environment* are the two most important journals for the GEE community. *Remote Sensing* published more than a quarter of GEE publications; however, articles published in *Remote Sensing of Environment* received more citations; and therefore have a bigger impact on the community; (4) Applications of GEE were diverse, focusing on land applications (LULC mapping, forestry, deforestation, urbanization and environmental monitoring), water resource applications (drought/flood mapping and lake/river monitoring), climate change, and crop mapping; and (5) Landsat imagery were the most popular satellite dataset, whereas random forest, decision trees, and support vector machines were the most popular machine learning algorithms used in GEE.

Limitations of the bibliometric analysis technique applied in this study have been discussed in previous publications (Eito-Brun 2018; Pham-Duc and Nguyen 2022). Here, we would like to emphasize the following points. First, we used only the Scopus database as input data; therefore, the publication collection does not contain all articles related to GEE available in the literature. In practice, combining Scopus and WoS databases, as discussed by Dao et al. (2022), is feasible; however, it involves a significant amount of data unification and repair, a process commonly known as data wrangling, as mentioned by Kumpulainen and Seppänen (2022). One more point worth noting is that the merged file can only be compatible with Biblioshiny software. In addition, other well-known and effective bibliographic software cannot be used, i.e., CiteSpace (Chen 2006), as it only takes input data derived from the WoS database. Second, data cleaning and data correction had been done manually before the analyzing steps; however, some information, especially names of Chinese scholars, cannot be corrected perfectly. This factor might affect the accuracy of our scholar collaboration network analysis. Third, as the number of publications related to GEE increases quickly, the analyses reported in this paper were correct only at the time of this study, and they will evolve and might be very different in the future. Therefore, this type of analysis should be conducted regularly, using up-to-date bibliographic data in order to closely observe the development of the GEE community.

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Author contributions Conceptualization: Binh Pham-Duc and Ho Nguyen; Methodology: Binh Pham-Duc and Ho Nguyen; Software: Binh Pham-Duc, Hien Phan and Quan Tran-Anh; Resources: Ho Nguyen, Hien Phan and Quan Tran-Anh; Data curation: Hien Phan and Quan Tran-Anh; Writing—original draft preparation: Binh Pham-Duc; Writing—review and editing: Binh Pham-Duc and Ho Nguyen; Visualization: Binh Pham-Duc; Project administration: Binh Pham-Duc. All authors have read and agreed to the published version of the manuscript.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no conflict of interest.

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