ORIGINAL PAPER

A bibliometric analysis on the visibility of the Sentinel-1 mission in the scientific literature

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Abstract

Seven years after the launch of the first Sentinel-1 satellite, its data have been widely used in the scientific community. This study provides the first quantitative analysis of the visibility of the Sentinel-1 mission to the scientific literature through a bibliometric analysis of 1628 articles published in scientific journals during the 2014–2020 period. The main findings show that the number of Sentinel-1 mission-related papers increased significantly over the years, with an annual growth rate of 83%. Remote sensing is the most popular journal where 31.75% of the publication collection has been published. China and the USA are the two most productive countries with a share of 22.30% and 16.22% in the collection. Research based on the Sentinel-1 data covered a wide range of topics in geoscience disciplines. The use of SAR interferometry, focusing on the studies of landslide, earthquake, ground deformation, and subsidence, is the most important research direction using Sentinel-1 data. Image fusion of Sentinel-1 and Sentinel-2 observations for mapping and monitoring applications is the second most important research direction. Other popular research areas are glaciology, soil moisture, agriculture, rice monitoring, and ship detection. This study uses bibliographic data derived only from the Scopus database; therefore, it might not cover all Sentinel-1 related documents. However, this paper is a good reference for researchers who want to use Sentinel-1 data in their studies. The two Sentinel-1 satellites will provide scientific data for years to come, meaning that this type of analysis should be done on a regular basis.

Introduction

Sentinel-1 is a satellite mission funded by the European Union and carried out by the European Space Agency (ESA). Sentinel-1 is also the first of the six missions that ESA is

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developing for the Copernicus initiative. It is a two-satellite constellation working at C-band (5.405 GHz), operating in four exclusive imaging modes with different spatial resolutions (the highest being 5 m) and swaths (up to 400 km). The first satellite (Sentinel-1A) was launched on April 3, 2014, and the second one (Sentinel-1B) was launched on April 22, 2016. Sentinel-1 satellites fly along a near-polar sun-synchronous circular orbit at an altitude of 693 km, with the incidence angles varying between 29° and 46°. The visiting time is 12 days with one satellite and reduces to 6 days with two satellites. Sentinel-1 satellites provide dual polarization capacities (HH, VV, HH + HV, and VV + VH), giving final users the ability to access a large variety of applications. Synthetic aperture radar (SAR) sensors equipped onboard the satellites allow observations day and night, regardless of the cloud cover, with spatial and temporal resolutions comparable to optical remote sensing (Brisco et al. 2008; Pham Duc and Tong Si 2021). This advantage of SAR sensors is extremely important for environmental monitoring projects, especially in tropical regions where the cloud contamination

can be very high during several months of the rainy season (Morel et al. 2012; Pereira et al. 2013; Dong et al. 2013; LIU et al. 2019). The major mission objectives of the satellites are shown in Table 1.

Today, 7 years after the successful launching of the first satellite, Sentinel-1 observations have been used widely worldwide, thanks to the ESA's policy to provide free-of-charge all data of the Copernicus program to the community. Since then, Sentinel-1 data has played an increasingly important role in earth studies (geoscience) including forest disturbance monitoring (Reiche et al. 2021), land-cover mapping (Pham et al. 2021), surface water monitoring (Pham-Duc et al. 2017), ground deformation monitoring (Lanari et al. 2020), soil moisture (Balenzano et al. 2021), land subsidence (Maghsoudi et al. 2021), and rapid damage assessment after a disaster (Plank 2014).

In this context, there is an urgent need for a descriptive analysis on the visibility of the Sentinel-1 data in the scientific literature as this type of analysis is still absent. Among different methods, bibliometric analysis, introduced by Pritchard (1969), is an effective approach for the quantitative investigation of scientific activities based on the form and content of the scientific literature (Broadus 1987). Nowadays, bibliometric analysis is widely applied to investigate the productivity and impact of scholars, research institutions, and countries in different research fields at global and local scales. For example, medicine (Tran et al. 2018, 2019), education (Hallinger and Chatpinyakoop 2019; Ha et al. 2020), social sciences (Pham-Duc et al. 2020b), industry 4.0 (Pham-Duc et al. 2021), paleopedology research field (Rykova and Busygina 2021), and water planning and management research (Almulhim et al. 2021). Some authors used bibliometric analysis to assess trends in the use of geographic information systems (GIS) in different disciplines (Fish and Piekielek 2016). In space research, several bibliometric studies have been available, focusing on analyses of journal scientific production (Xia et al. 1999), or some

research directions related to space science such as GPS technology (Wang et al. 2013), and aerodynamics (Rezadad and Maghami 2014). Other authors focused on bibliometric analysis of space agencies (Taşkın and Aydinoglu 2015; Martin and Beaudry 2015; Eito-Brun and Ledesma Rodríguez 2016) or analyzed the visibility of other satellite missions, for instance, the CryoSat mission (Eito-Brun 2018). Recently, remote sensing research also received great attention in bibliometric analysis (Zhang et al. 2017; Kandus et al. 2018; Duan et al. 2020; Pham-Duc et al. 2020a), as well as in systematic review (Hemati et al. 2021). These papers all reported rapid growth in the number of publications in these research fields, in general, and in the field of space science and applications of satellite remote sensing specifically.

Findings from this work provide quantitative information about the development of scientific papers, its main contributors, the most popular scientific journals, the most important funding sponsors, and the most popular research topics in this research field. This information could be useful for researchers or newcomers as more and more scholars will be working in this field thanks to the availability of satellite data based on the Open Access policy of ESA and other major space agencies. To derive this information, we intend to answer the following research questions:

1. What was the annual growth rate of Sentinel-1 mission-related documents?
2. Which scientific journals have published the most articles?
3. Which were the most productive countries, institutions, and scholars publishing in this field?
4. Who were the most important funding sponsors?
5. What were the most influential articles?
6. What were the most important and popular research topics using Sentinel-1 data?

Table 1 Major objectives of the Sentinel-1 missions and recent publications in these research directions

	Major objectives	Recent publications
1	Land monitoring of forests, water, soil, and agriculture	(Hemati et al. 2021; Ygorra et al. 2021; Pham Duc and Tong Si 2021)
2	Emergency mapping support in the event of natural disasters	(Carreño Conde and De Mata Muñoz 2019; Funning and Garcia 2019)
3	Marine monitoring of the maritime environment	(Rikka et al. 2018)
4	Sea ice observations and iceberg monitoring	(Soldal et al. 2019; Chen et al. 2021, p. 1)
5	Production of high-resolution ice charts	(Park et al. 2020)
6	Forecasting ice conditions at sea	(de Gélis et al. 2021)
7	Mapping oil spills	(Chaturvedi et al. 2020; El-Magd et al. 2021)
8	Sea vessel detection	(Dechesne et al. 2019)
9	Climate change monitoring	(Wagner et al. 2021)

Materials and methods

The methodology applied in this study follows the guidelines introduced in Pham-Duc et al. (2020b), which was based on bibliometric analysis. This method measures the scientific activities of Sentinel-1 mission-related papers, based on statistical measurements of quantitative data derived from the scientific literature. Although Web of Science and Scopus are the two largest bibliographic databases, the Scopus database was selected as the search engine for this study due to its wider coverage and detailed indexing (Eito-Brun 2018).

The search query (Box 1) was conducted in the Scopus database (https://www.scopus.com/) on 10 May 2021. All documents that contained the keyword "Sentinel-1" in the titles, abstracts, or keywords were searched, with the time limited to the 2014–2020 period as the first Sentinel-1A satellite was launched in April 2014. Next, all publications written in languages other than English were excluded. As the quality of conference papers is not consistent, we limited our analysis to only journal articles and review papers, and other document types were excluded from the publication collection. Titles and abstracts of the publication collection were manually screened by the authors to ensure that all documents were actually related to the Sentinel-1 mission. The final output collection of journal articles and review papers was exported in BIB and CSV formats for post-processing in two different bibliometric analysis tools which are highly effective and popular for this kind of study: Biblioshiny (Aria and Cuccurullo 2017) and VOSviewer (van Eck and Waltman 2010). Biblioshiny is an open-source tool for executing a comprehensive science mapping analysis of scientific literature. This tool was programmed in the R environment that provides the ability to be flexible and facilitate integration with other statistical and graphical packages, as well as the flexibility to be quickly upgraded and integrated. VOSviewer is a free Java tool, designed for analyzing and visualizing citation networks of scientific collections. This tool displays the graphical representation of bibliometric maps and is especially effective for illustrating large bibliometric maps in an easy-to-interpret manner. Using both Biblioshiny and VOSviewer allows us to have a comprehensive overview of the scientific development of this research field, based on the number of published papers, the number of citations, h-index (Alavifard 2015), collaboration networks of countries and authors, and co-occurrence network of keywords.

Box 1 The search query string.

Results

Annual growth of documents

According to our retrieved results, there were 2989 Sentinel-1-related documents of all document types published in the Scopus database during the 2014–2020 period (Fig. 1, pie chart). The number of documents was refined to 1628 by limiting the language to English and document type to articles and review papers. Articles ($n=1609$) accounted for 54%, while review papers only accounted for 0.6% of the publication collection ($n=19$). The main information of the publication collection is shown in Table 2. The collection of 1628 publications was published in 254 different sources, by 4966 authors, with 8368 author appearances. There were 37 single authors who published only 43 papers (2.65%) in the collection. On average, each document has 10.23 citations (16,659 citations in total), 3.05 authors, and 5.14 co-authors, while each author has an average of 0.33 documents. The development of annual numbers of documents during the 2014–2020 period is illustrated in Fig. 1 - bar chart, showing a significant increase, with an average annual growth rate of 83%. Starting with 17 and 25 publications in 2014 and 2015, the annual publication increased to 60 in 2016 and 156 in 2017. The recent 3 years accounted for 84.15% of the collection, with 272 documents in 2018; 458 documents in 2019; and 640 documents in 2020, respectively.

Journals published the most articles

The publication collection was published in 254 different journals (Table 2), and the list of the top ten publishing journals by numbers of articles and citations is shown in Table 3, along with their publishing houses, h-indices, quartiles, and impact factors. *Remote Sensing* ranked first, with outstanding contribution to both numbers of papers ($n=517$; 31.75%) and citations ($n=5549$; 33.30%), followed by *Remote Sensing of Environment* with 90 papers (5.58%) and 1468 citations (8.81%), and *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* (JSTAEORS) with 68 papers (4.17%) and 825 citations (4.95%). *IEEE Transactions on Geoscience and Remote Sensing* (TGRS) and *International Journal of Remote Sensing* (IJRS) were in the fourth and fifth positions, with 53 and 52 papers, and 840 and 484 citations, respectively. The remaining five journals published between 23 and 37 papers

TITLE-ABS-KEY (Sentinel-1) AND PUBYEAR > 2013 AND PUBYEAR < 2021 AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "re"))

Fig. 1 The pie chart illustrates the percentage of document types of the collection. The bar chart illustrates the annual number of documents, and its cumulative number
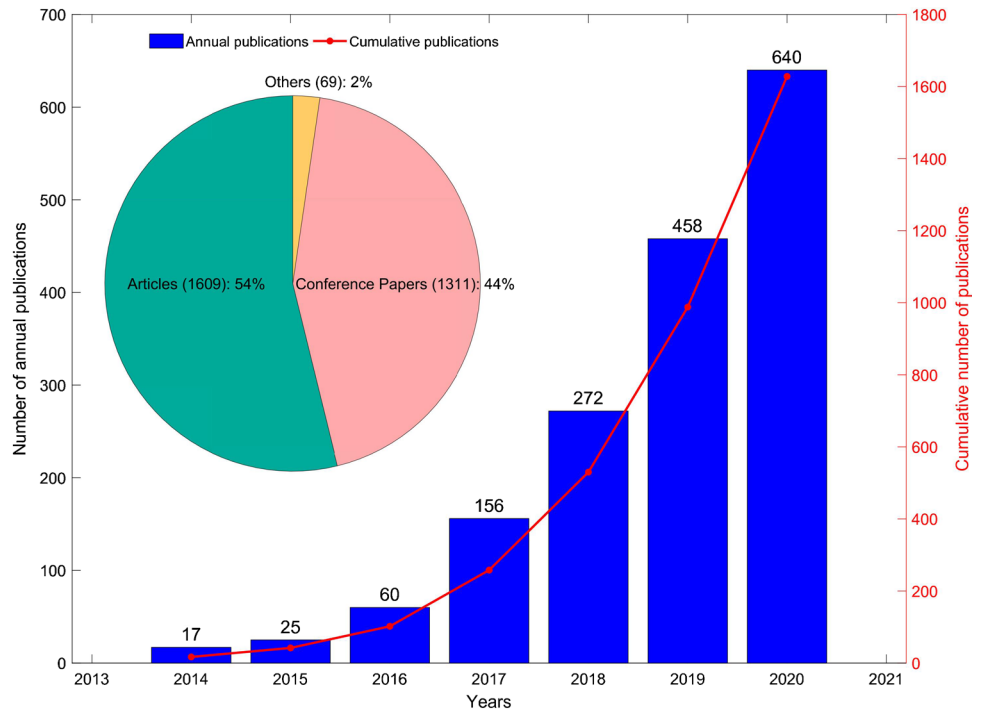

Table 2 Main information of articles and review papers in the publication collection, published in the Scopus database during the 2014–2020 period

Description	
Articles	1609
Reviews	19
Sources	254
Period	2014–2020
Authors	4966
Author appearances	8368
Authors of single-author documents	37
Authors of multi-author documents	4929
Single-authored documents	43
Average citations per document	10.2
Authors per document	3.05
Co-authors per document	5.14
Documents per author	0.33

during this period, with a total of 2608 citations or a share of 15.65%. Based on the h-index, *Remote Sensing* ($n=35$) and *Remote Sensing of Environment* ($n=20$) were also in the first two positions. JSTAEORS and TGRS shared the third position, with an h-index of 16, while the h-index of the remaining six journals varies from 10 to 12. According to information from the *SCImago Journal & Country Rank* 2020, all journals in Table 3 were classified into the first quartile of their journal categories. The top ten journals published a total of 942 papers or a share of 57.92% of the

collection, with 11,774 citations or a share of 70.68% of the total number of citations. Among the top ten journals, three belong to the IEEE, three to the Elsevier, two to the Multidisciplinary Digital Publishing Institute (MDPI), one to the Wiley-Blackwell, and one to the Taylor & Francis publishing house.

Annual numbers of publications of the top ten journals are shown in Fig. 2. The contribution of *Remote Sensing* started to rise quickly in 2016, and more and more accounted for a larger share in recent years. The ratio of numbers of papers between *Remote Sensing* and other journals in the top ten increased gradually over the years, starting at 0.73 in 2016 to 1.1 in 2017, 0.96 in 2018, 1.37 in 2019, and 1.45 in 2020, respectively. The increased contribution of *Remote Sensing of Environment* in the recent 2 years was notable; however, the number of papers published in this journal only accounted for around 10% of annual publications by the top ten journals.

Bibliographic coupling among the top ten journals, determined based on the number of references they shared, is illustrated in Fig. 3. Each node represents a journal, and the size of nodes is proportional to their number of publications, while the thickness of lines between nodes is proportional to the strength of bibliographic coupling between journals. As expected, *Remote Sensing* is in the center of the network, with strong bibliographic couplings with other journals in the top ten. The strength of bibliographic coupling between *Remote Sensing* and *Remote Sensing of Environment* is the largest, followed by the coupling between *Remote Sensing* and *JSTAEORS*, and between *Remote Sensing* and *Sensor*.

Table 3 Ranking of the top ten journals by a number of documents

Order	Journals	Publishing house	No. of articles	%	No. of citations	%	h-index	Quartile*	Impact factor 2020
1	Remote Sensing (**RS**)	MDPI	517	31.75	5549 (#1)	33.3	35	Q1	4.84 (#5)
2	Remote Sensing of Environment (**RSE**)	Elsevier	90	5.58	1468 (#2)	8.81	20	Q1	10.16 (#1)
3	IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing (**JSTAEORS**)	IEEE	68	4.17	825 (#4)	4.95	16	Q1	3.78 (#8)
4	IEEE Transactions on Geoscience and Remote Sensing (**TGRS**)	IEEE	53	3.25	840 (#3)	5.04	16	Q1	5.6 (#4)
5	International Journal of Remote Sensing (**IJRS**)	Taylor & Francis	52	3.19	484 (#7)	2.90	10	Q1	3.15 (#10)
6	IEEE Geoscience and Remote Sensing Letters (**GRSL**)	IEEE	37	2.27	782 (#5)	4.69	12	Q1	3.96 (#7)
7	Sensors	MDPI	37	2.27	468 (#8)	2.80	12	Q1	3.57 (#9)
8	Geophysical Research Letters (**GRL**)	Wiley-Blackwell	34	2.08	578 (#6)	3.46	12	Q1	4.72 (#6)
9	ISPRS Journal of Photogrammetry and Remote Sensing (**JPRS**)	Elsevier	31	1.90	394 (#9)	2.36	10	Q1	8.98 (#2)
10	International Journal of Applied Earth Observation and Geoinformation (**IJAEOG**)	Elsevier	23	1.41	386 (#10)	2.31	12	Q1	5.93 (#3)

*According to the *SCImago Journal & Country Rank* (https://www.scimagojr.com/) 2020

Countries published the most articles

The collection of 1628 papers was published by scholars from 117 different countries or territories (hereafter referred to as "countries" for simplification). A list of the top ten
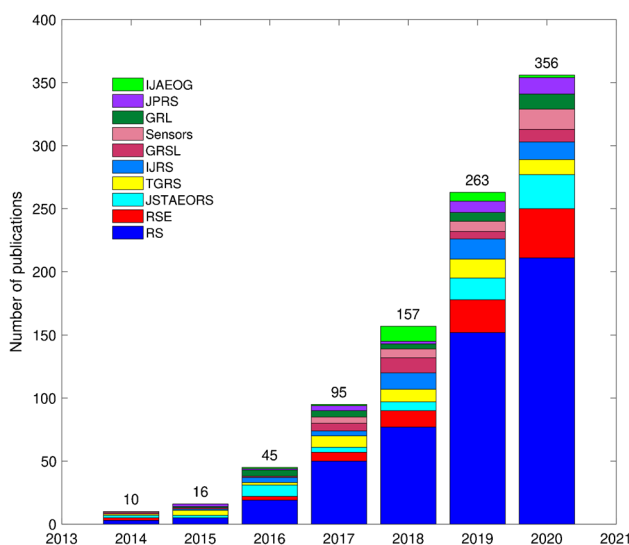
Fig. 2 Annual numbers of publications of the top ten journals are in Table 3

most productive countries is shown in Table 4, along with their number of citations. With more than 200 papers from each country, China ($n=363$), the USA ($n=264$), Italy ($n=261$), and Germany ($n=211$) were in the first four positions. France ($n=150$) and the UK ($n=144$) were in the fifth and sixth positions with more than 140 publications. Spain ($n=96$), Canada ($n=77$), India ($n=70$), and the Netherlands ($n=65$) were in the next positions with less than 100 publications for each country. The top ten countries published a total of 1276 papers which accounted for 78.38% of the publication collection. Based on the numbers of citations, the USA ranked first with 3660 citations (21.97%), followed by Italy with 3295 citations (19.77%). China moved from the first position, by a number of publications, to the third position, by a number of citations ($n=2833$ or a share of 17%). Except for the Netherlands which was in the tenth position based on the number of publications, but in the eighth position based on the number of citations, the order of the other countries remained unchanged.

Visualization of the international cooperation network between 54 countries, which published at least five publications, is shown in Fig. 4. Each country is represented by a node, and the size of nodes indicates the number of publications, while the thickness of lines between nodes indicates the strength of collaboration between

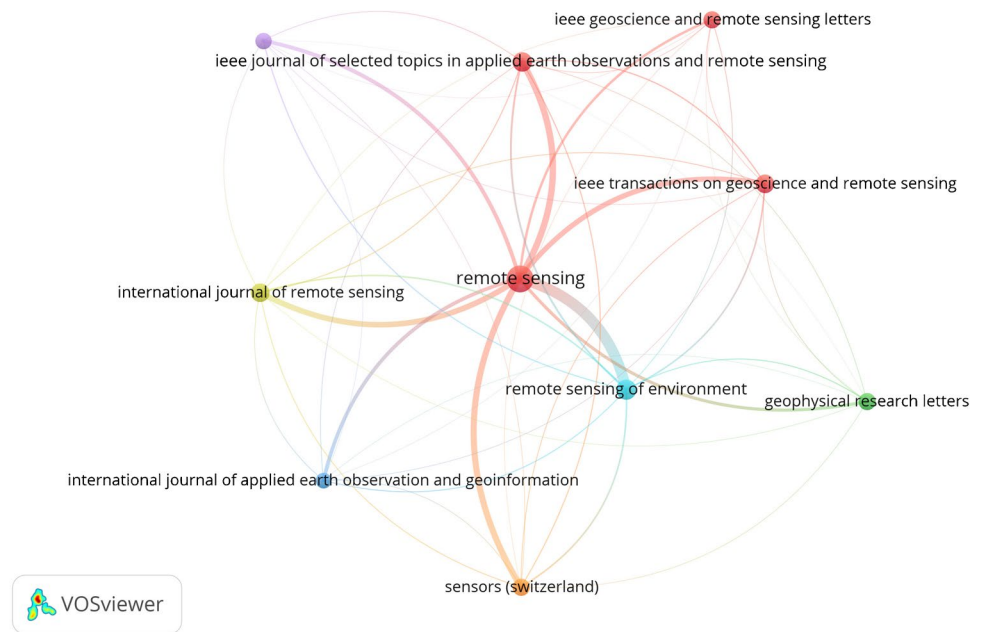**Fig. 3** Bibliographic coupling among the top ten journals in Table 3

Institutions published the most articles

The ranking of the most productive institutions, by a number of documents, is shown in Table 5. China and France both have three representatives, but French institutions were all in the bottom half of Table 5 (including, CNRS–55 papers, CESBIO–45 papers, and University of Montpellier–38 papers), while two over three Chinese institutions (Chinese Academy of Sciences–85 papers and Wuhan University–66 papers) were in the first and third positions. The University of Chinese Academy of Sciences was the other Chinese representative, being in the seventh position with 45 papers. The USA has two representatives, being in the ninth and tenth positions which were the Jet Propulsion Laboratory (JPL–36 papers) and California Institute of Technology (Caltech–34 papers). It is worth mentioning that JPL and Caltech have a strong connection and collaboration as JPL is under the management of Caltech for the National Aeronautics and Space Administration (NASA). The two remaining institutions in the top ten were the German Aerospace Center (DLR) in the second position with 81 papers and the National Research Council (CNR) of Italy in the fourth position with 66 papers. The top ten most productive institutions published a total of 416 papers or a share of 25.55% of the publication collection.

Scholars published the most articles

The ranking of the top ten most productive scholars, by a number of papers, is shown in Table 6, along with their number of citations, their h-indices, their institutions, and their main research areas. Note that one scholar can be affiliated
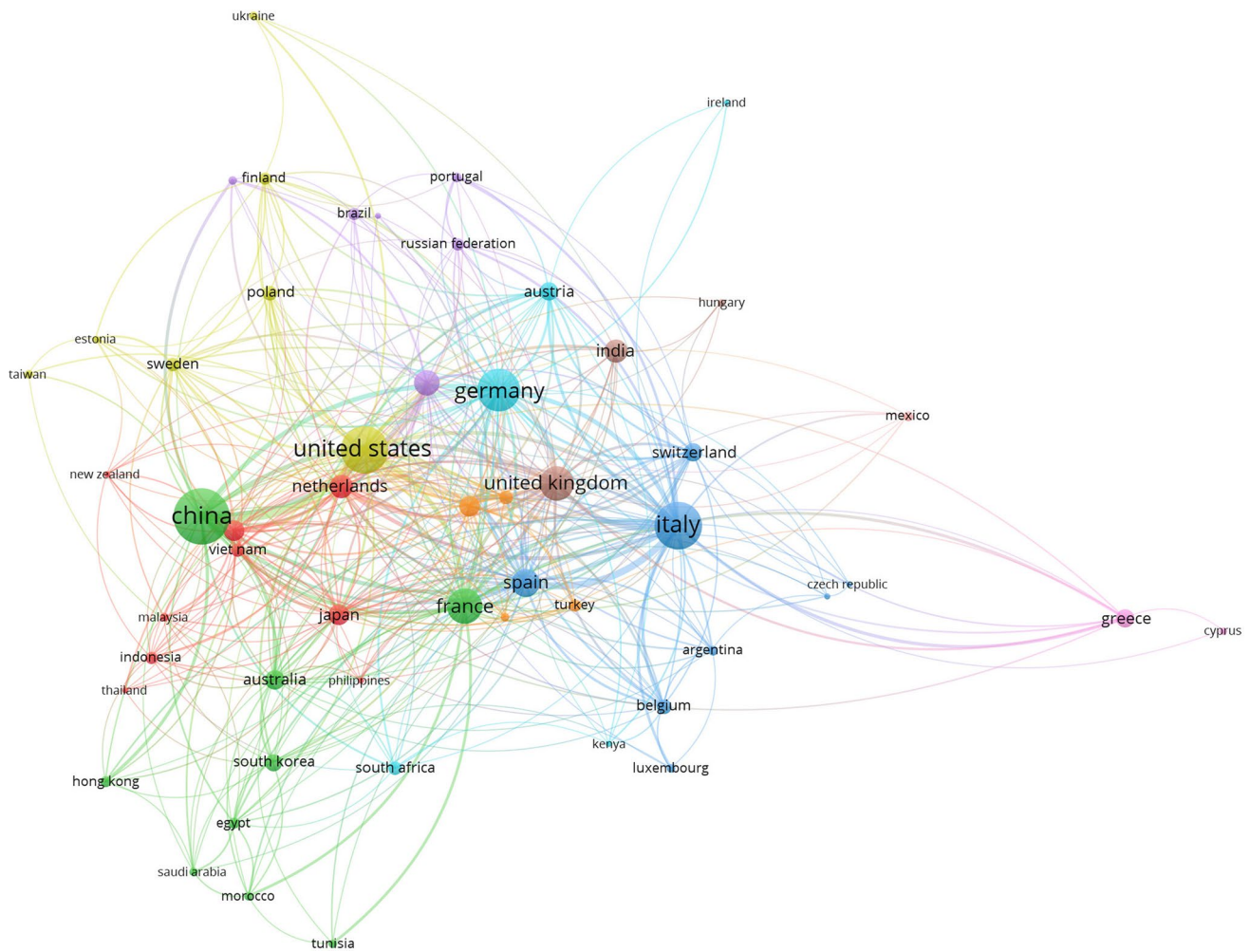
Table 4 Ranking of the most productive countries by a number of documents

Order	Country	Total papers	%	Total Citations	%
1	China	363	22.30	2833	17.00 (#3)
2	USA	264	16.22	3660	21.97 (#1)
3	Italy	261	16.03	3295	19.77 (#2)
4	Germany	211	12.96	2493	14.96 (#4)
5	France	150	9.21	2311	13.87 (#5)
6	UK	144	8.84	1768	10.61 (#6)
7	Spain	96	5.60	1342	8.05 (#7)
8	Canada	77	4.73	803	4.82 (#9)
9	India	70	4.30	295	1.77 (#10)
10	Netherlands	65	3.99	1132	6.79 (#8)

these countries. It is as expected that the top ten countries in Table 4 are clearly visible in the center of the collaboration network. China and France formed the biggest cluster (green) with nine countries. The Netherlands and other Asian countries (Iran, Japan, Vietnam, Indonesia, Thailand, Malaysia, and the Philippines) formed the second-largest cluster (red). Italy and Spain were in the center of their cluster (blue) with six other countries, including Switzerland, Belgium, Luxembourg, Czech Republic, Argentine, and Peru. The UK and India had a close collaboration to form another cluster (brown). Finally, the USA, Germany, and Canada were in the center of their clusters, with various collaborations with other countries.

Fig. 4 International cooperation network of 54 countries published at least five articles. Each node represents a country. The size of nodes is proportional to the number of publications, while the thickness of lines between nodes is proportional to the strength of collaboration between these countries

Table 5 Ranking of the most productive institutions by a number of documents

Order	Institutions	Country	No. of articles	%
1	Chinese Academy of Sciences	China	85	5.22
2	German Aerospace Center (DLR)	Germany	81	4.98
3	Wuhan University	China	66	4.05
4	National Research Council (CNR)	Italy	62	3.80
5	National Centre for Space Studies (CNRS)	France	55	3.38
6	Center for the Study of the Biosphere from Space (CESBIO)	France	45	2.76
7	University of Chinese Academy of Sciences	China	45	2.76
8	University of Montpellier	France	38	2.34
9	Jet Propulsion Laboratory	USA	36	2.21
10	California Institute of Technology	USA	34	2.08

with several institutions; however, their addresses shown in Table 6 were collected from their most recent publications. Baghdad N. ranked first with 30 papers, followed by Zribi M. with 27 papers, Casagli N. with 22 papers, and Solari L. with 21 papers. The fifth and sixth positions belong to Raspini F. and Bianchini S. with 17 papers for each scholar.

Table 6 Ranking of the most productive scholars by a number of documents and their main research areas

Order	Author	Institution/country	No. of articles	No. of citations	h-index	Main research area
1	Baghdad N	University of Montpellier/**France**	30	626 (#1)	14	Soil moisture, vegetation, crops
2	Zribi M	CESBIO, University of Toulouse/**France**	27	606 (#2)	14	Soil moisture, soil survey, vegetation
3	Casagli N	University of Firenze/**Italy**	22	406 (#3)	10	Landslide, deformation, interferometry
4	Solari L	CTTC/CERCA/**Spain**	21	352 (#5)	11	Deformation, interferometry, landslide
5	Raspini F	University of Firenze/**Italy**	17	385 (#4)	10	Deformation, landslide, interferometry
6	Bianchini S	University of Firenze/**Italy**	17	305 (#6)	10	Interferometry, deformation, landslide
7	Lanari R	National Research Council (CNR)/**Italy**	16	277 (#8)	10	Deformation, D-inSAR, earthquake
8	Monserrat O	CTTC/CERCA/**Spain**	16	249 (#9)	9	Interferometry, deformation, InSAR
9	Wagner W	Vienna University of Technology/**Austria**	14	283 (#7)	10	Soil moisture, soil survey, forestry
10	Xu C	Wuhan University/**China**	14	91 (#10)	4	Earthquake, deformation, fault slips

Lanari R. and Monserrat O. were in the next positions with 16 papers for each scholar, while Wagner W. and Xu C. were in the ninth and tenth positions with 14 papers for each scholar. The top ten most productive scholars published a total of 120 papers, with 2092 citations, which accounted for 7.37% of the publication collection, and 12.56% of the total number of citations. Except for the first four scholars,

the numbers of papers of other scholars in Table 6 were very close; therefore, their orders might change quickly in the future. Among the top ten scholars, Italy has four representatives, France and Spain have two, and Austria and China have one. As seen in the production over time of the top ten scholars (Fig. 5), except for Wagner W. and Lanari R. who published their first Sentinel-1 mission-related papers
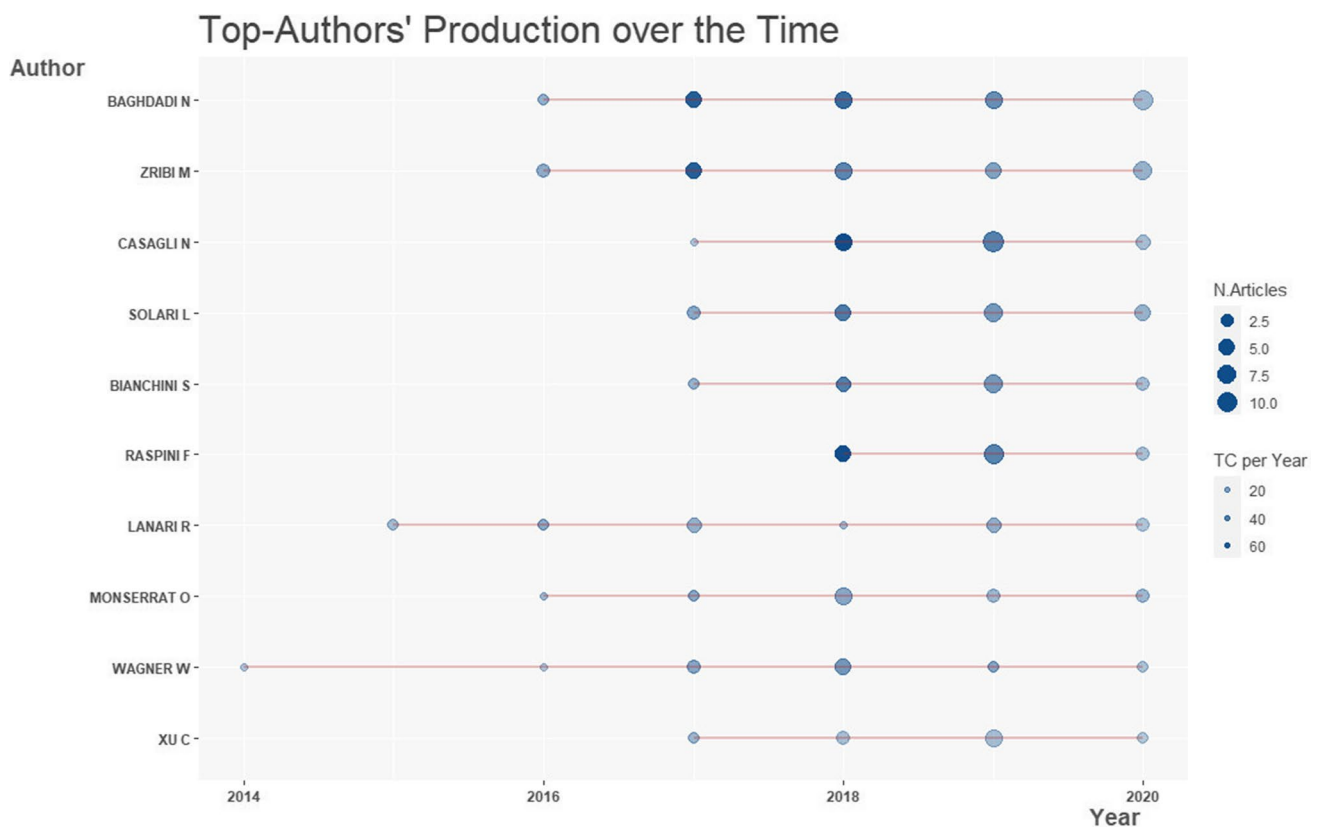
Fig. 5 Production over time of the top ten most productive scholars in Table 6

in 2014 and 2015, respectively, all other scholars in the top ten started publishing Sentinel-1 mission-related papers in 2016 and 2017. Since then, all scholars in the top ten have been published regularly.

The collaboration network of the 100 most productive scholars with at least seven papers is shown in Fig. 6. Each scholar is represented by a node, and the size of nodes is proportional to the number of their publications. The thickness of lines between nodes is proportional to the collaboration strength between scholars, determined by the number of publications they appeared together as co-authors. Scholars are grouped into clusters, represented by different colors, and the position of a scholar within the constellation indicates how frequent their co-occurrence was with other scholars. There are five main clusters. The biggest one (red) includes 34 scholars, mostly from China or with Chinese origin (based on their names). The second largest one (green) includes 13 scholars, with five scholars from Italy and Spain listed in Table 6, including Casagli N., Solari L., Bianchini S., Raspini F., and Monserrat O. The third cluster (blue) has 12 scholars mostly from China, the USA, and the UK, but none of them belong to the top ten most productive scholars in Table 6. The fourth cluster (yellow) includes nine scholars, and Lanari R. is the only scholar in the top ten who is classified in this cluster. Baghdad N. and Zribi M., the two most productive scholars, along with four other scholars, formed the fifth cluster. Other small groups and isolated scholars in Fig. 6 had no or little connections with

the five main clusters; however, every single author had at least seven publications related to the Sentinel-1 mission at the time of this study.

Most important funding sponsors

A list of the top ten most important funding sponsors is shown in Table 7. China, the European Union, and the USA have three funding sponsors for each country/organization, and the last one (CNRS) belongs to France which funded 39 projects. The National Natural Science Foundation of China funded the most number of projects ($n = 242$). This is more than the total number of projects funded by ESA ($n = 147$) and the National Aeronautics and Space Administration ($n = 86$). Other sponsors in Table 7 funded between 30 and 50 projects related to the Sentinel-1 mission during the 2014–2020 period.

Most influential articles

A list of the top ten most cited documents in the collection is shown in Table 8, with additional information such as the publishing journals, first author's institutions and countries, and the main research area of each paper. The total number of citations of the top ten most cited documents was 1644 at the time of this study which accounted for 9.86% of the total citations of the publication collection. The article described a multilevel deep learning architecture

Fig. 6 Collaboration network of 100 scholars with at least seven publications. Each node represents a scholar. The size of nodes is proportional to the number of publications, while the thickness of lines between nodes is proportional to the strength of collaboration between co-authors
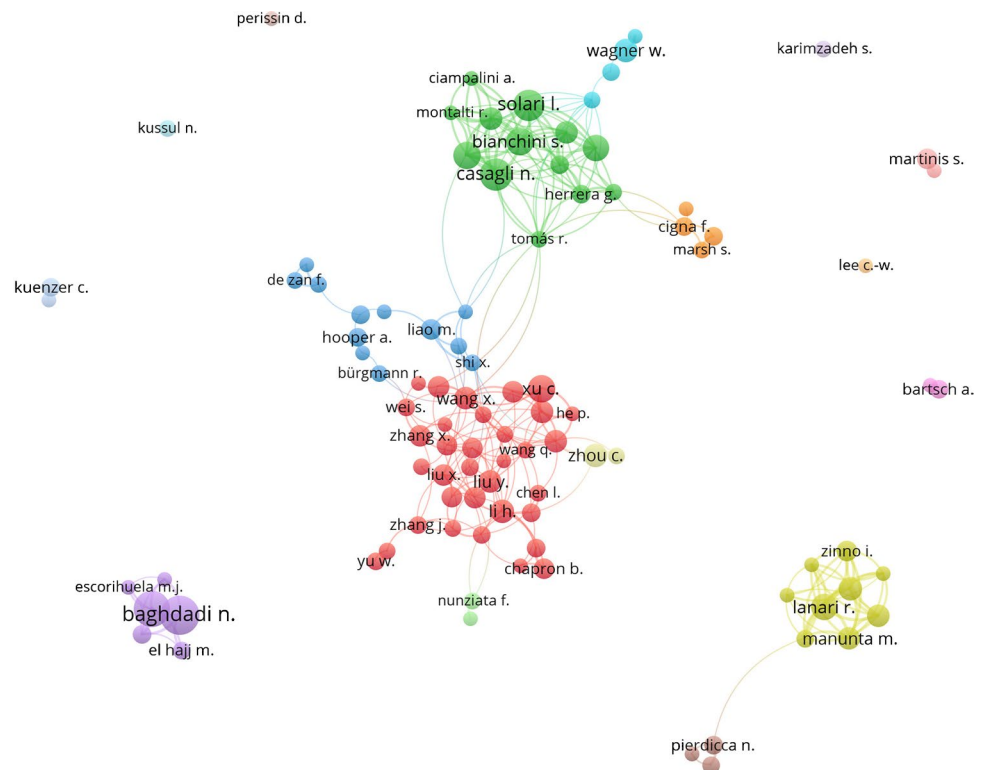
Table 7 Ranking of the most important funding sponsors

Order	Funding sponsor	Country/ organization	No. of projects
1	National Natural Science Foundation of China	China	242
2	European Space Agency	EU	147
3	National Aeronautics and Space Administration	USA	86
4	European Commission	EU	51
5	Ecological Society of America	USA	50
6	National Basic Research Program of China	China	46
7	National Centre for Space Studies	France	39
8	National Science Foundation	USA	37
9	Fundamental Research Funds for the Central Universities	China	32
10	Horizon 2020 Framework Programme	EU	29

for land cover and crop types classification using Sentinel-1 and Landsat-8 observations (Kussul et al. 2017) ranked first with outstanding numbers of citations ($n = 434$) and yearly average citations ($n = 108.5$). In the second position, with 197 citations, is an article studying landslides and unstable slopes using multi-temporal interferometry from different radar satellites, then introducing the potential of Sentinel-1 observations for future studies (Wasowski and Bovenga 2014). There are three articles with more than 150 citations at the time of this study, focusing on three different research areas using Sentinel-1 observations including interferometry (Yagüe-Martínez et al. 2016), crop monitoring (Veloso et al. 2017), and flood monitoring (Twele et al. 2016). Except for the article at the tenth position with 98 citations, all other publications in Table 8 received more than 110 citations at the time of this study.

There are three articles with the first author's affiliation with the German Aerospace Center and two articles with the first author's affiliation with CESBIO in France. There are two articles having the first author's affiliation located in the USA, while the three remaining articles having the first author's affiliation located in Ukraine, Italy, and China. Among the top ten most cited articles, four of them have been published in *Remote Sensing*, and two in *Remote Sensing of Environment*, while the four remaining articles have been published in four different journals.

Figure 7 shows the historical direct citation network of 38 most located cited papers of the publication collection. Each article is represented by a node, and each line between two nodes indicates a direct citation between two articles. Important papers related to similar research topics were identified and coded in the same colors. Combining information in Table 8 and Fig. 7, core and most important publications having the most influence to the community can be listed, such as (Wasowski and Bovenga 2014; Yagüe-Martínez et al. 2016; Twele et al. 2016; Kussul et al. 2017; Veloso et al. 2017; Torbick et al. 2017).

Analysis of research topics using Sentinel-1 data

The co-occurrence network of the 100 most popular keywords in the publication collection is shown in Fig. 8. Each node represents a keyword, and thickness of lines between nodes represents the strength of the relationship between keywords, which was determined by the frequency they appeared together in publications. Related keywords are grouped in different clusters coded by different colours (note that keywords Sentinel-1, Synthetic Aperture Radar, and SAR were not included in the network as they appeared in almost all papers of the collection). InSAR is the most popular keyword of the biggest cluster (red) containing articles using radar interferometry techniques to study landslides, land subsidence, earthquake, and deformation. Sentinel-2 is the most popular keyword of the second biggest cluster (blue) which includes publications studying image fusion using Sentinel-1 and Sentinel-2 images or combining Sentinel-1 and Sentinel-2 images for mapping and monitoring applications, or for forestry and deforestation, and flood monitoring. Keywords in the green cluster indicate that Landsat-8 and MODIS observations are often being used with Sentinel-1 data for crop mapping and crop classification, as well as to study the biomass. Keywords in the yellow cluster suggest that many papers have used Sentinel-1 data for glaciology (such as sea ice, arctic, and permafrost), especially in Greenland. Tools and processing techniques that are popular for processing Sentinel-1 images can be named as Google Earth Engine, neural network, machine learning, deep learning, random forests, and support vector machine. Some other research topics using Sentinel-1 data that are visible in Fig. 8 are soil moisture, agriculture, rice monitoring, and ship detection. Vietnam, with the Mekong Delta, is identified as one of the most popular study areas for rice studies using Sentinel-1 data.

Table 8 Ranking of the most influential publications by number of citations

Title	Authors	Source	First author's institution/country	Research area	Year	No. of citations	Yearly average citations
Deep learning classification of land cover and crop types using remote sensing data	Kussul, Nataliia Lavreniuk, Mykola Skakun, Sergii Shelestov, Andrii	IEEE Geoscience and Remote Sensing Letters	National Academy of Sciences of Ukraine/**Ukraine**	Deep learning/crop type classification	2017	434	108.5 (#1)
Investigating landslides and unstable slopes with satellite multi-temporal interferometry: current issues and future perspectives	Wasowski, Janusz Bovenga, Fabio	Engineering Geology	National Research Council/**Italy**	Landslide	2014	197	28.15 (#6)
Interferometric processing of Sentinel-1 TOPS data	Yagüe-Martínez et al. 2016	IEEE Transactions on Geoscience and Remote Sensing	German Aerospace Center/**Germany**	Inter-ferometric	2016	159	31.80 (#4)
Understanding the temporal behavior of crops using Sentinel-1 and Sentinel-2-like data for agricultural applications	Veloso, Amanda Mermoz, Stéphane Bouvet, Alexandre Le Toan, Thuy Planells, Milena Dejoux, Jean-François Ceschia, Eric	Remote Sensing of Environment	CESBIO/**France**	Crop monitoring	2017	158	39.50 (#2)
Sentinel-1-based flood mapping: a fully automated processing chain	Twele, André Cao, Wenxi Plank, Simon Martinis, Sandro	International Journal of Remote Sensing	German Aerospace Center/**Germany**	Flood monitoring	2016	151	30.20 (#5)
Development and assessment of the SMAP enhanced passive soil moisture product	Chan et al. 2018	Remote Sensing of Environment	Jet Propulsion Laboratory/**USA**	Soil moisture	2018	115	38.30 (#3)
Contextual region-based convolutional neural network with multilayer fusion for SAR ship detection	Kang, Miao Ji, Kefeng Leng, Xiangguang Lin, Zhao	Remote Sensing	National University of Defense Technology/**China**	Ship detection	2017	111	27.75 (#7)
Rapid damage assessment by means of multi-temporal SAR-A comprehensive review and outlook to Sentinel-1	Plank, Simon	Remote Sensing	German Aerospace Center/**Germany**	Damage mapping	2014	111	15.85 (#10)
Monitoring rice agriculture across Myanmar using time series Sentinel-1 assisted by Landsat-8 and PALSAR-2	Torbick, Nathan Chowdhury, Diya Salas, William Qi, Jiaguo	Remote Sensing	Applied Geosolutions/**USA**	Rice mapping	2017	110	27.50 (#8)
Improved early crop type identification by joint use of high temporal resolution SAR and optical image time series	Inglada, Jordi Vincent, Arthur Arias, Marcela Marais-Sicre, Claire	Remote Sensing	CESBIO/**France**	Crop type identification	2016	98	19.60 (#9)

Discussion and conclusions

The annual number of Sentinel-1 mission-related papers has increased significantly over the years, with an annual growth rate of 83%, indicating the potential to grow rapidly in the future (see Fig. 1). The contribution of the recent 3 years (2018–2020) was remarkable with 1370 papers which accounted for 84.15% of the publication collection. The recent creation of supporting services such as the ESA's Research and User Support (RUS) service, or the NASA's Applied Remote Sensing Training Program (ARSET) could be an explanation for this increase because these services are very useful for the scientific community as it provides not only free and open access data, but also advices in satellite data processing, powerful computing environment through virtual machines, and comprehensive hands-on training service. This is a great source for scholars, especially newcomers with no or little experience in working with satellite data and satellite observations. Unfortunately, the RUS service was terminated at the end of 2021.

As a result of the source growth analysis, the number of publications related to the Sentinel-1 mission published in *Remote Sensing* is significant, especially in the last 3 years. It is expected that the contribution of *Remote Sensing* in this field will continue to increase in the future. Short publication time (average 18 days since submission to first decision) could be one of the reasons to explain why many scholars prefer to submit their work to *Remote Sensing*, knowing that the average rejection rate of this journal was 57.5% for the 2017–2020 period. This domination of *Remote Sensing* and *Remote Sensing of Environment* can also be observed with other satellite observations (Hemati et al. 2021).

Considering the country's contribution, it is important to note that the two most productive countries (China and the USA) are not members of the European Union (EU), and the scientific output related to the Sentinel-1 mission of China was outstanding compared to other countries. Canada and India are the two other countries in Table 4 who also do not belong to the EU. Research projects using satellite data from space missions are complex and require strong international collaboration which is clearly seen in the cooperation network in Fig. 4. The collaboration networks between China and the USA, China and Germany, Germany and Italy, Italy and Spain, and France and the USA were the backbone of this research area. As a consequence, the top ten most productive research institutions (Table 5) all belong to the top five countries in Table 4. One reason for the dominion of China and the USA is that these countries provide numerous funding for Sentinel-1-related-missions (Table 7).

Considering the author contribution (Table 6), nine of the ten most productive scholars are from the EU member countries, including four in Italy, two in France, two in Spain, and one in Austria. Combined with information from the co-author collaboration network (see Fig. 5), it suggests that there are several strong research institutions and universities in the EU member countries where most of Sentinel-1-related documents have been conducted by a few research groups. In China, the number of Chinese scholars who are working on Sentinel-1-related research is numerous, thanks to the availability of various funding such as from the National Natural Science Foundation and the National Basic Research Program. However, these Sentinel-1-related research projects were also conducted by a few research groups and they are all linked together. In addition, Chinese scholars have massive collaboration networks with scholars from all other countries, but their connections with scholars from the USA and the UK were strongest.

By analyzing titles and research areas of the top ten most cited papers in the collection (Table 8), it is possible to identify potential research directions that might attract more attention from the community. For example, there are three papers in Table 8 investigated the use of Sentinel-1 and optical images (for example, Sentinel-2, Landsat-8) for crop monitoring and crop type classification (Inglada et al. 2016; Kussul et al. 2017; Veloso et al. 2017). Other papers in Table 8 cover different research directions using Sentinel-1 observations and data, for instance, landslide (Wasowski and Bovenga 2014), interferometry (Yagüe-Martínez et al. 2016), flood monitoring (Twele et al. 2016), soil moisture (Chan et al. 2018), ship detection (Kang et al. 2017), damage mapping (Plank 2014), and rice mapping (Torbick et al. 2017). This suggests that research based on the Sentinel-1 data covered a wide range of topics of geoscience disciplines. Deeper analysis of the co-occurrence network of the 100 most popular keywords in Fig. 8 confirms that research topics using Sentinel-1 observations were diverse. Several main Sentinel-1-related research areas received more attraction from the community can be listed such as (1) using InSAR technique for landslide, land subsidence, ground deformation, and earthquake; (2) image fusion of Sentinel-1 and optical satellite observations for crop mapping and crop types classification; and (3) glaciology. However, keywords related to some major Sentinel-1 mission objectives are not visible in Fig. 8, for instance, marine monitoring, oil spill mapping, and sea vessel detection. This suggests that future work should focus more on these research directions.

To summarize, bibliometric analysis has been used in this study to give the first quantitative statistic of the visibility of the Sentinel-1 mission to the scientific literature. The number of publications increased significantly, especially over the last 3 years (2018–2020). *Remote Sensing* is the most popular journal, and the number of papers published in this journal is expected to increase quickly in coming years. Although most of the productive authors are from Europe (in
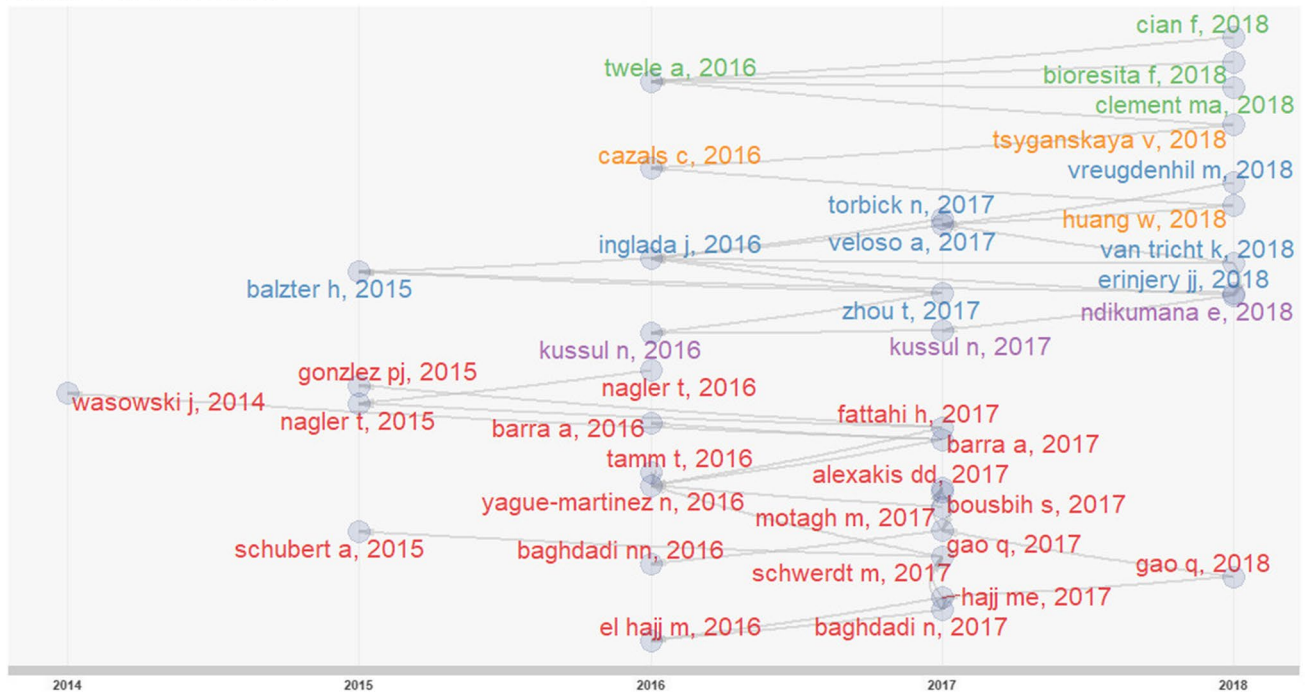
Historical Direct Citation Network

Fig. 7 Historical direct citation network of 38 most local cited articles in the publication collection. Each article is represented by a node, and each line between two nodes represents a direct citation. Nodes are plotted on an oriented graph where the horizontal axis represents the publication years

Fig. 8 Co-occurrence network of the 100 most popular keywords in the publication collection. Each node represents a keyword, and thickness between nodes represents the strength of the relationship between keywords which was determined by the frequency they appeared together in publications
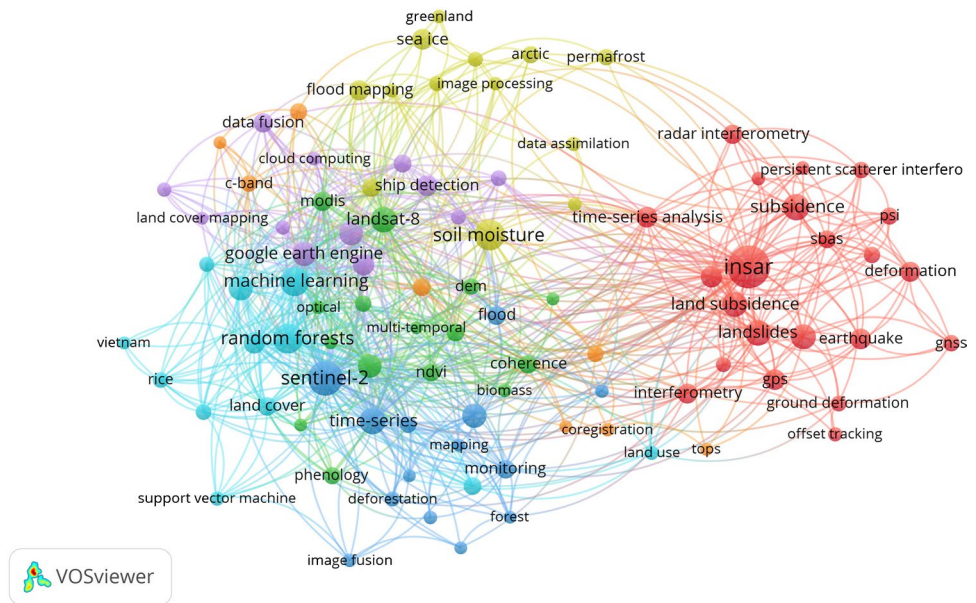
France, Italy, Spain, and Germany), China and the USA were the most important contributors with the highest number of Sentinel-1-related papers. Research topics were diverse, focusing on InSAR technique for landslide, earthquake, land subsidence, and land deformation, image fusion of Sentinel-1 and optical satellite images for mapping and monitoring applications, glaciology, soil moisture, ship detection, agriculture, and rice monitoring.

Limitation

In this study, we acknowledge some limitations that result from the data collection procedure and the limitations of the analysis tools. The approach used in this study shows some limitations which have been reported in previous papers (Eito-Brun 2018; Pham-Duc et al. 2020a). First, the bibliometric analysis was conducted using only data from the Scopus database. The Scopus database is the biggest one, but it might not cover all Sentinel-1-related documents. Comparisons with results derived from other bibliographic databases, such as the Web of Science, will help to cross validate findings from this study (Rykova and Busygina 2021). Second, some information on the Scopus database is not standardized, especially for authors' names and authors' affiliations. Data scanning and data cleaning had been done before conducting the analysis, but manual correction for every paper in the collection is impossible. This is one of the main factors that may bring inaccuracy to the analysis. Third, quantitative analyses of documents published in conferences might provide some useful information, but it was not done in this study. Fourth, analysis tools in VOSviewer and Biblioshiny are very effective to achieve a deep understanding of a research field, but they are not perfect and some types of analysis (for example, gender analysis) are not available due to technical limitations. Finally, it is important to note that all analyses presented in this study only represent the visibility of the Sentinel-1 mission in the literature at a given time.

The two Sentinel-1 satellites are still orbiting and providing continuous data to the community for years to come. This means that information reported in this paper will evolve and be different in the future, at least until the end of the satellite mission. It suggests that bibliometric analysis of the Sentinel-1 mission should be conducted on a regular basis, to monitor the evolution and development of its visibility in the community. It is worth mentioning that a systematic review of Sentinel-1 data in different applications is necessary to investigate the usage of Sentinel-1 in these directions, and how it has improved the accuracy as compared to optical remote sensing and other sources.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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