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RESEARCH ARTICLE

Knowledge mapping on the sun-induced chlorophyll fluorescence technology research: a scientometric and visualization analysis

Ming Li[1,4,5] · Yang Wang[1,3,5] · Na Li[5] · Bin Chen[2] · ShurenChou[3]

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Abstract

The sun-induced chlorophyll fluorescence (SIF) has received increasing attention over the past few years. This scientometric study analyzed the SIF research field, based on publications available in Web of Science Core Collection visualization, and cluster analysis enabled us to map the knowledge domain and intellectual landscape of this field and identify thematic trends, landmark articles, and emerging research themes. In this study, the software VOSviewer and CiteSpace were used to identify the intellectual base and research front using visualization and analysis. Then, we analyzed synthesized networks of co-authorship (author, institution, and country), co-citation (author, document, and journal), and co-occurring keywords. SIF has increased its publication output steadily since 2002. This study provided a visual knowledge map of the major research domains of SIF. Also, explanations and implications of the findings were explored, and the emerging trends were identified. This report provides a thorough overview of the current state and growth trends of SIF research, and it helps researchers and practitioners understand the major areas of attention in this area and provides insights into prospective areas for further study.

Keywords Sun-induced chlorophyll fluorescence · Remote sensing · Visualization · Scientometric

Introduction

Monitoring plant health and function from space is vital for precision farming, forest management, and carbon budget assessments. Many earth observing systems provide reflectance data as part of their optical remote sensing (RS) strategy, which provides estimates of plant status based on the structural or biochemical attributes of plants. Sun-induced chlorophyll fluorescence (SIF) has been considered a promising proxy for gross primary productivity (GPP) in recent years (Sun et al. 2017; Yang and Tol 2018; Zhang et al. 2018). However, there are some challenges from diurnal to seasonal, from the leaf to the landscape, and from active to passive fluorescence (Porcar-Castell et al. 2014; Cogliati et al. 2015; Liu et al. 2016; Kimm et al. 2021). GPP is an important component of the global carbon cycle (Schickling et al. 2016; Miao et al. 2018). Estimates of the spatial and temporal distributions of GPP at regional to global scales are critical to the understanding of the climate-carbon cycle feedback (Xia 2015; Zhang et al. 2016; Zheng et al. 2017; Chang et al. 2022).

Some studies have found that the accuracy of estimating GPP by sunlit SIF or shaded SIF leaves is different (He et al. 2017; Pinto et al. 2016). A model was developed to quantify the fractions of sunlit and shaded leaves in the sensor's field of view on clear days, to normalize remotely sensed SIF to the hotspot direction ($SIF_{hotspot}$), and to compute the canopy-level total SIF (SIF_{canopy}), in order to accurately estimate the total GPP (He et al. 2017). Also, SIF–GPP linear models are usually adopted to calculate global or regional GPP from satellite SIF data (Guanter et al. 2014). It was found that

Responsible Editor: Philippe Garrigues

✉ ShurenChou
chou666@163.com

[1] Gong Qing Institute of Science and Technology, Nanchang 330044, China

[2] Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

[3] Space Security Center, Space Engineering University, Beijing 101416, China

[4] Jilin Academy of Agricultural Sciences, Changchun 130016, China

[5] School of Civil and Environmental Engineering, Jilin Jianzhu University, Changchun, China

SIF increased with the increase of APAR (Zhang et al. 2012; Zhou et al. 2016). The SIF from the sunlit leaves is higher than the values from the shaded leaf group because of the larger APAR values of sunlit leaves. Canopy total SIF comes mostly from the sunlit leaf group (Pinto et al. 2016, 2017; Damm et al. 2010).

Previous studies have shown that ground-based measured SIF can be used as a direct probe of photosynthesis in plants (Meroni et al. 2009). In temperate deciduous forests, SIF was considered to be a good detector of diurnal and seasonal GPP (Yang et al. 2015). There is confirmation that ground-based SIF can be used as a proxy for GPP since it directly correlates with APAR, LUE, and thus GPP. For the leaf perspective, ϕF (the quantum yield of fluorescence in PSII) are affected by photochemical (PQ) and non-photochemical quenching (NPQ). In the field, the PAM system is used to measure fluorescence (active methods). The leaf-scale SIF is related to LUE and APAR (Porcar-Castell et al. 2014). ϕF is related to ϕP (the quantum yield of photochemistry in PSII) and hence to LUE (Chou et al. 2017). To sum up, many scholars have carried out a large number of theoretical and application studies on SIF in the past 10 years and achieved a large number of research results.

Scientometric based on mathematical and statistical knowledge carries out quantitative analysis on the existing literature, sorting out the development of the discipline and the changes of research hotspots in terms of the number of articles published in the discipline, the research countries and institutions, the distribution of keywords, authors and periodicals (Li et al. 2022; Qin et al. 2022). At present, it has been widely used in Environmental Science, Material Science, Energy Science, and other fields and has become an important tool to summarize the historical research process and predict the future development trend (Li et al. 2022; Qin et al. 2022; Gómez-Marín and Bridgwater 2021;). However, there is still no research on SIF by scientometric to date.

In order to gain a deeper understanding of global SIF trends, this study provides a comprehensive analysis of SIF by scientometric and visualization, providing references and ideas for future researchers on SIF. Hence, this study mainly focuses on the following aspects: (1) analysis of the number of papers published, using a quantitative visualization report to understand the changes in the number of papers published each year and the distribution of the number of papers published in different countries; (2) analyzed the publications and cooperation of important authors, institutions, and journals in this field and dig out and analyze the literature with important influence in this field; and (3) through using the software CiteSpace, clustering of keywords, time zone distribution, timeline representation, and emergent analysis of recent 5 years. The results provide valuable visualization information on the evolution process, development trends, frontiers, and hotspots of SIF for researchers.

Methods

Literature search strategy and database formulation

We select the Web of Science Core Collection as the database to obtain literature, which includes the Science Citation Index (SCI-E), Social Science Citation Index (SSCI), Arts and Humanities Citation Index (A&HCI), and Conference Citation Index (CPCI), covering more comprehensive literature on a wide range of topics. We comprehensively searched the Web of Science Core Collection database as follows: (1) the search topic (TS) = "solar-induced chlorophyll fluorescence" or "solar induced chlorophyll fluorescence" or "sun-induced chlorophyll fluorescence" or "sun induced chlorophyll fluorescence", (2) the searching time from 2005 to 2021, (3) the searching language was English, and (4) a total of 506 publications were obtained in this field, after excluding other types of literature such as reviews and meeting. Finally, 429 publications were reserved for this study.

Scientometric analysis

The software VOSviewer (V 1.6.18) and CiteSpace (V 5.8.R3) were used in this study, which are the most common and widely used visualization software. The software VOSviewer is a tool for building and visualizing bibliometric networks. Also, it has been widely used in the field of bibliometric analysis (Qin et al. 2022; Gómez-Marín and Bridgwater 2021). These networks can be constructed based on citations, bibliographic coupling, co-citations, and co-authors. It also provides text-mining capabilities that can be used to build and visualize co-occurrence networks of important terms extracted from a large body of scientific literature. The software CiteSpace is a tool for identifying and presenting new trends and developments in the scientific literature. It can visualize the relationship in the literature in the form of a scientific knowledge graph, which helps to sort out past research trajectories and to predict future prospects (Li et al. 2022; Qin et al. 2022).

Results and discussion

Characteristics of publications and research areas

Through the search of the Web of Science Core Collection database, 429 research articles about SIF were published from 2005 to 2021. SIF publication trends and the main subject categories from the Web of Science Core Collection are shown in Fig. 1. From 2005 to 2012, although there were some fluctuations in the research on SIF topics

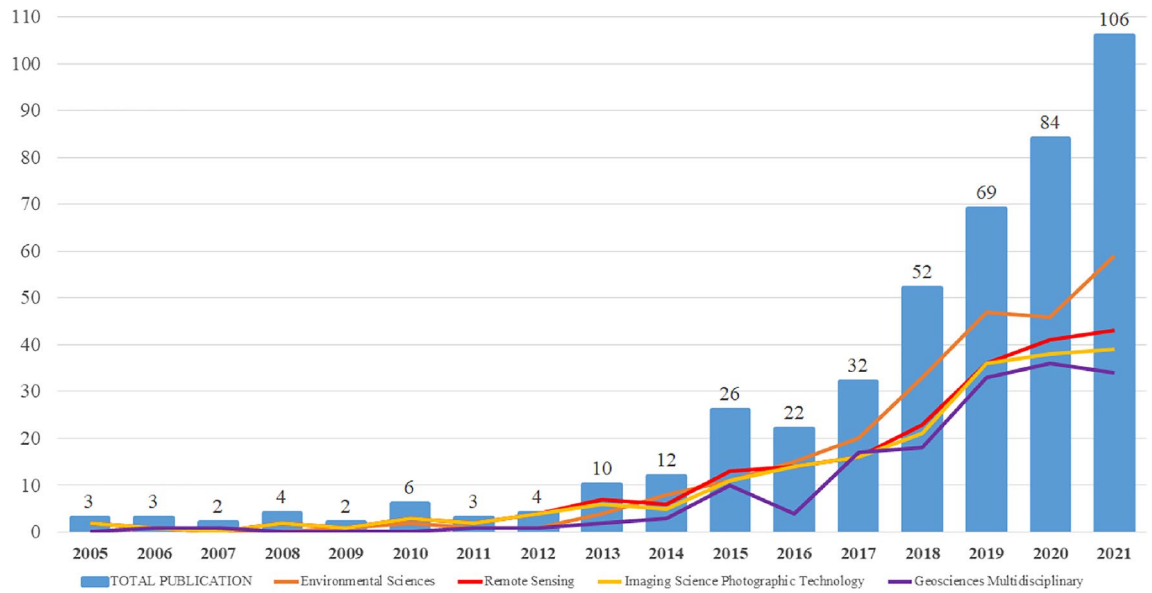

Fig. 1 The annual total number of articles published during 2005–2021 and the interannual variation of literature types

over time, the number of publications was small, with an average of about 3. From 2013 to 2021, except that the number of papers published in 2016 was slightly lower than that in 2017, the number of research papers increased rapidly, which was highly valued by scientists. It can be seen that 413 of the 429 papers were published during this period, accounting for 93.86% of all research papers. In recent years, the research of SIF has become one of the most active frontier fields in the field of remote sensing.

Through the analysis of subject categories, the top four subject categories in the number of documents are environmental sciences ($n = 249$), remote sensing ($n = 214$), imaging science photographic technology ($n = 201$), and geosciences multidisciplinary ($n = 161$). It is not difficult to see that in the above research fields, the research of SIF shows a rapid growth trend. From 2013 to 2021, most subject categories of the published SIF research were environmental science and remote sensing. For example, 249 research papers of environmental science disciplines account for 56.59% of the published papers of 34 disciplines in all SIF research fields, more than one-third of SIF research papers (36.59% of the total records) were published in geosciences multidisciplinary disciplines, and the number of research papers on SIF published on remote sensing and imaging science photographic technology is the same, accounting for 48.63% and 45.68% of the total records, respectively.

In order to explore influential journals in SIF research, we summarize and visualize the source journals of literature samples. The results are shown in Fig. 2 and Table 1. The minimum number of articles and the minimum number of citations of VOSViewer are set to 5 and 50, respectively. Of the 82 source journals identified, 16 meet the threshold and are included in the composite network (Fig. 2).

Table 1 lists the top 10 journals that published SIF research papers in the past 17 years. The number of articles published by these ten journals listed in the table accounts for 67.27% (296 research papers) of all publications. The circulation of papers in various journals shows the diversity of journals and disciplines. In the past 17 years, most journals (about 89%) published less than 10 papers, with *Remote Sensing of Environment* ranking first with 85 articles, followed by *Remote Sensing* with 79 articles. Their contribution to SIF research is 27.37%. The third most influential and dynamic journal is *Agricultural and Forest Meteorology*, which published 28 articles, about one-third of the number of articles published by *Remote Sensing of Environment*. *Geophysical Research Letters* and *Journal of Geophysical Research-Biogeosciences* rank fourth, with 24 articles, and the rest are *Global Change Biology* (16 articles), *Biogeosciences* (11 articles), *IEEE Transactions on Geoscience and Remote Sensing* (10 articles), *Science of The Total Environment* (10 articles), and *International Journal of Applied Earth Observation and Geoinformation* (9 articles). These journals are comprehensive journals covering most SIF studies.

From other quantitative expressions in Table 1, it can be concluded that *Global Change Biology*, *Remote Sensing of Environment*, and *Geophysical Research Letters* are more influential in the field of SIF research. Although the journal *Remote Sensing* published many articles on SIF research, its average number of standardized citations is not high, indicating that the annual average citations of the journal are not the most influential. The average

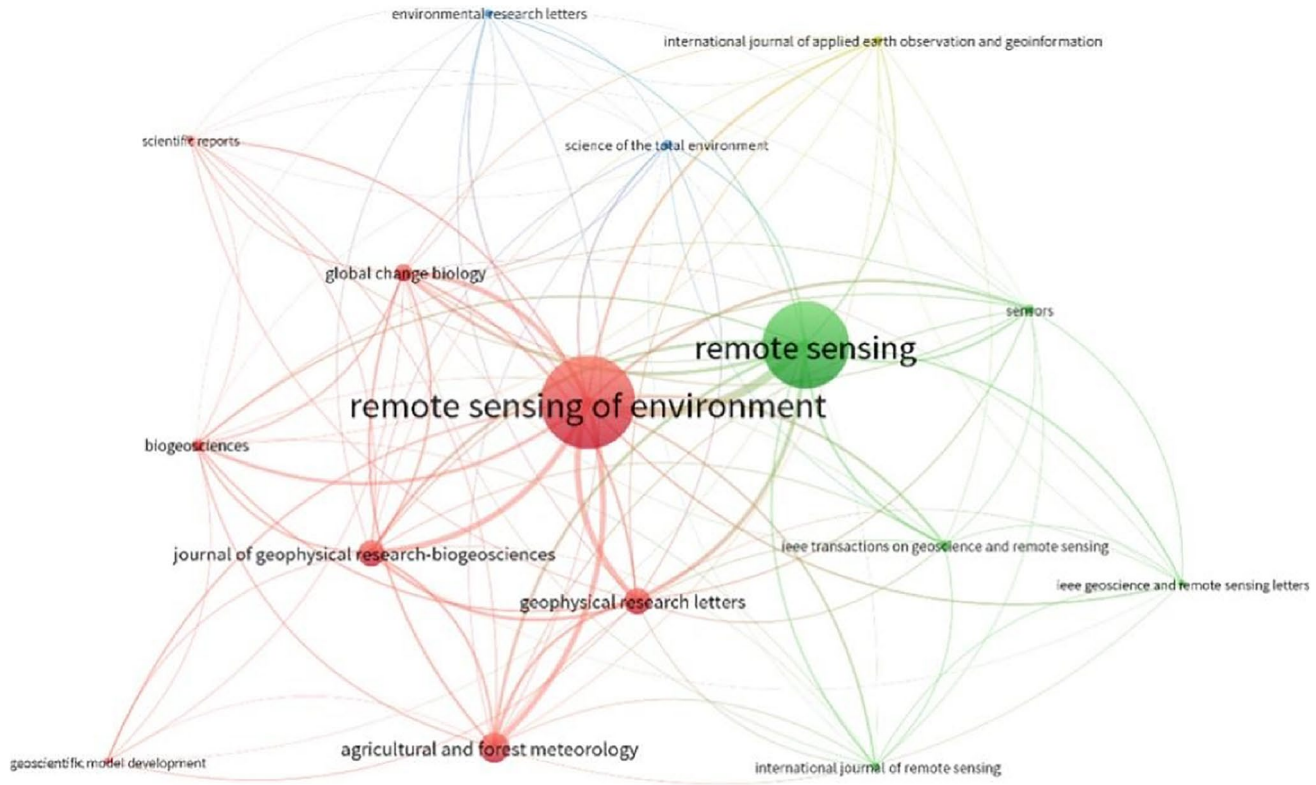

Fig. 2 Visualization of main journals that published SIF research

Table 1 Quantitative analysis of journal sources in SIF research

Journal	Documents	Citations	Total link strength
Remote Sensing of Environment	85	4568	2024
Remote Sensing	79	1048	1280
Agricultural and Forest Meteorology	28	483	546
Geophysical Research Letters	24	1165	733
Journal of Geophysical Research-Biogeosciences	24	624	587
Global Change Biology	16	920	524
Biogeosciences	11	328	264
IEEE Transactions on Geoscience and Remote Sensing	10	286	173
Science of the Total Environment	10	131	106
International Journal of Applied Earth Observation and Geoinformation	9	170	135

publication year refers to the average year of publication for articles published in a given journal. It can be seen that *Remote Sensing*, *Agricultural and Forest Meteorology, Journal of Geophysical Research-Biogeosciences*, and *International Journal of Applied Earth Observation and Geoinformation* have published corresponding articles in the field of SIF research in recent years. The journal *IEEE Transactions on Geoscience and Remote Sensing* has published fewer articles in this research field in recent years.

The articles with the largest number of citations and the greatest impact are determined by setting the minimum number of citations to 100. Thirty-seven of the 429 articles exceed this threshold in VOSViewer (Fig. 3).

Taking the total number of citations as an index, the impact and quality are evaluated by the number of standard citations. Table 2 summarizes the 10 most cited research articles and their related parameters in SIF research in the past 17 years. In this study, 429 publications are cited 14,314

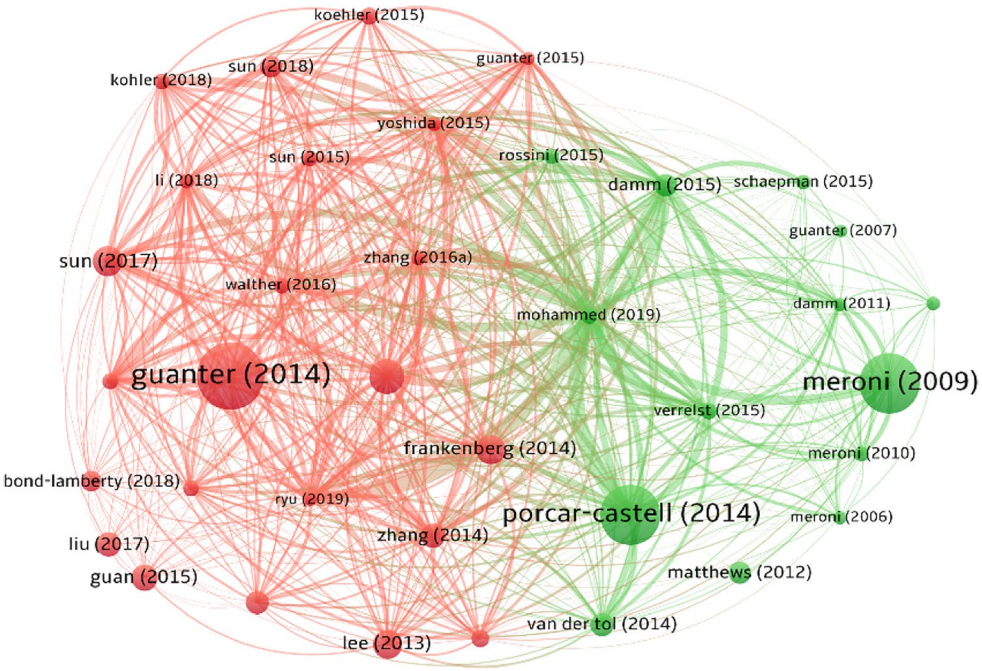

Fig. 3 Visualization of influential articles in SIF research

Table 2 Quantitative analysis of highly influential articles in SIF research

Document	Title	Source	Citations	Total link strength
Guanter et al. (2014)	Global and time-resolved monitoring of crop photosynthesis with chlorophyll fluorescence	*PANS*	531	269
Porcar-Castell et al. (2014)	Linking chlorophyll *a* fluorescence to photosynthesis for remote sensing applications: mechanisms and challenges	*Journal of Experimental Botany*	478	415
Meroni et al. (2009)	Remote sensing of solar-induced chlorophyll fluorescence: review of methods and applications	*Remote Sensing of Environment*	474	172
Yang et al. (2015)	Solar-induced chlorophyll fluorescence that correlates with canopy photosynthesis on diurnal and seasonal scales in a temperate deciduous forest	*Geophysical Research Letters*	275	386
Sun et al. (2017)	OCO-2 advances photosynthesis observation from space via solar-induced chlorophyll fluorescence	*Science*	241	300
Frankenberg (2011)	Prospects for chlorophyll fluorescence remote sensing from the Orbiting Carbon Observatory-2	*Remote Sensing of Environment*	234	236
Lee et al. (2013)	Forest productivity and water stress in Amazonia: observations from GOSAT chlorophyll fluorescence	*Proceedings of The Royal Society B-biological Sciences*	231	191
Guan et al. (2015)	Photosynthetic seasonality of global tropical forests constrained by hydroclimate	*Nature Geoscience*	210	63
Zhang et al. (2014)	Estimation of vegetation photosynthetic capacity from space-based measurements of chlorophyll fluorescence for terrestrial biosphere models	*Global Change Biology*	196	297
Liu et al. (2017)	Contrasting carbon cycle responses of the tropical continents to the 2015–2016 El Niño	*Science*	190	40

of citation times and 7639 of citation times without self-citation, with an average of 32.53 per article, of which 37 articles are cited only once. The 10 most cited articles are cited 3060 of citation times, accounting for 21.38% of the total number of citations, which shows the important role of these 10 articles in SIF research. Luis Guanter published a research article in the journal PNAS entitled Global and time-resolved monitoring of crop photosynthesis with chlorophyll fluorescence, which is cited 531 times from 2005 to 2021, ranking the first (Guanter et al. 2014). At the same

time, the average number of citations per year in this article is also the highest (66.75). However, the number of articles on SIF research published in the journal where this article is located is not in the top 10. This article mainly demonstrates that spaceborne SIF retrievals provide a direct measure of the GPP of cropland and grassland ecosystems. This study uses SIF observation to provide a global perspective on agricultural productivity. "Linking chlorophyll*a* fluorescence to photosynthesis for remote sensing applications: mechanisms and challenges" published by Porcar-Castell is the second most cited article, with 478 citations. "Remote sensing of solar-induced chlorophyll fluorescence: Review of methods and applications" by Meroni has been cited 474 of citation times. It can be seen that the journal where the article is located is also the journal with the largest number of articles published in this field. Among the 10 most cited articles, 7 were published in 2013 and 2014. Therefore, these 2 years are very important for the development of knowledge systems in SIF research.

Collaboration: co-author network analyses

Author co-authorship

The minimum number of published articles and the minimum number of citations of articles were set to 10 and 100 in VOSViewer, respectively. As a result, 42 of 1650 authors met the inclusion criteria. We analyzed the network of authors' publications in the existing research field (Fig. 4).

Table 3 Quantitative analysis of influential authors in SIF research

Author	*h*-index	Documents	Citations
Joseph A. Berry	92	20	2393
Jing M. Chen	87	15	320
Zhang Yongguang	76	39	1859
Christian Frankenberg	75	39	3208
Liu Liangyun	67	33	648
Luis Guanter	56	35	2921
Christiaan Van Der Tol	55	24	1756
Joanna Joiner	52	22	2601
Rascher, Uwe	49	24	737
Liu Xinjie	38	27	550
Sergio Cogliati	34	21	595

The *h*-index of authors was from Web of Science

Table 3 lists the top 10 authors with the largest number of published papers. They have published more than 20 papers to determine the core strength of SIF in the field of remote sensing. Among the top 10 authors, only two are from Asian countries, and the others are from Western countries. Christian Frankenberg and Zhang Yongguang are the two authors with the largest number of published articles, both of whom have published 39 research papers, accounting for 8.86% of all articles. Luis Guanter has published 35 articles

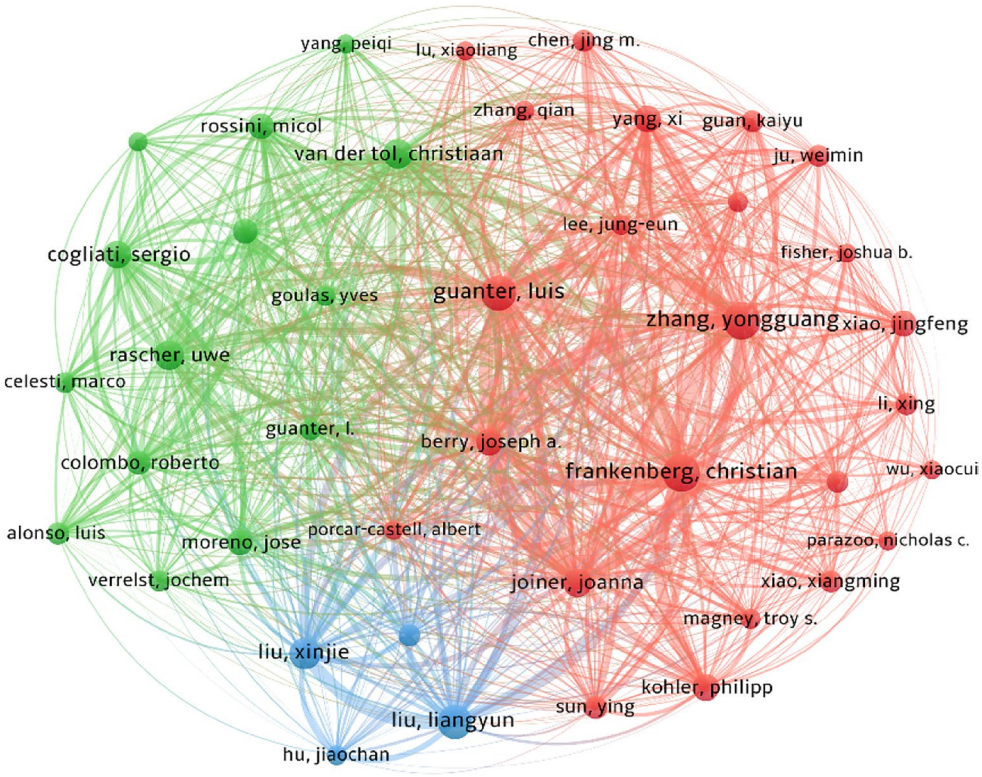

Fig. 4 Mapping of authors in the SIF research

(accounting for 7.95%), ranking third. Liu Liangyun and Liu Xinjie from China have published 33 articles (accounting for 7.5%) and 27 articles (accounting for 6.14%), respectively. The remaining five authors published between 20 and 24 articles. It can be found that Joseph A. Berry and Jing M. Chen, although the number of published articles is not the largest in SIF research, have been influential in the field.

The authors who met the threshold were analyzed cooperatively, and their visualization is shown in Fig. 5. As can be seen from the figure, the network is mainly composed of six clusters. Each cluster represents a cooperative group. The author Luis Guanter represents a cluster, which reflects that the author has less cooperation with other authors. The authors Xiao Jingfeng and Li Xing belong to a cluster, and their cooperation with other authors is also low. It is not difficult to see that these two authors only cooperate with individual authors of the red cluster represented by Christian Frankenberg and Luis Guanter and do not cooperate with the authors in other clusters. The remaining green clusters are represented by Christiaan Van Der Tol and Rascher, Uwe, the yellow clusters are represented by Liu Liangyun and Liu Xinjie, the blue clusters are represented by Jing. M Chen and Weimin Ju, and the author groups in the above red clusters have carried out extensive cooperation.

Institution co-authorship

A total of 563 academic institutions from different countries participated in the research on SIF. In the analysis, the minimum number of published articles and the minimum number of citations of articles of each institution are set to 5 and 50, respectively. As a result, 78 of the 563 different institutions meet the standard. The number of documents issued by institutions in the existing research field was analyzed (Fig. 6).

Table 3 shows the number of published papers, standard citations, average year of publication, and average standard citations of the top 10 institutions from 2005 to 2021. Among the top 10 institutions, the USA has the largest number of institutions, with three in total, two in China and Germany, and one in Italy, Spain, and the Netherlands. Although France, Australia, Canada, and Switzerland are more influential countries, the above ten more influential research institutions will come from these four countries in the future. It can also be seen from Table 5 that eight of

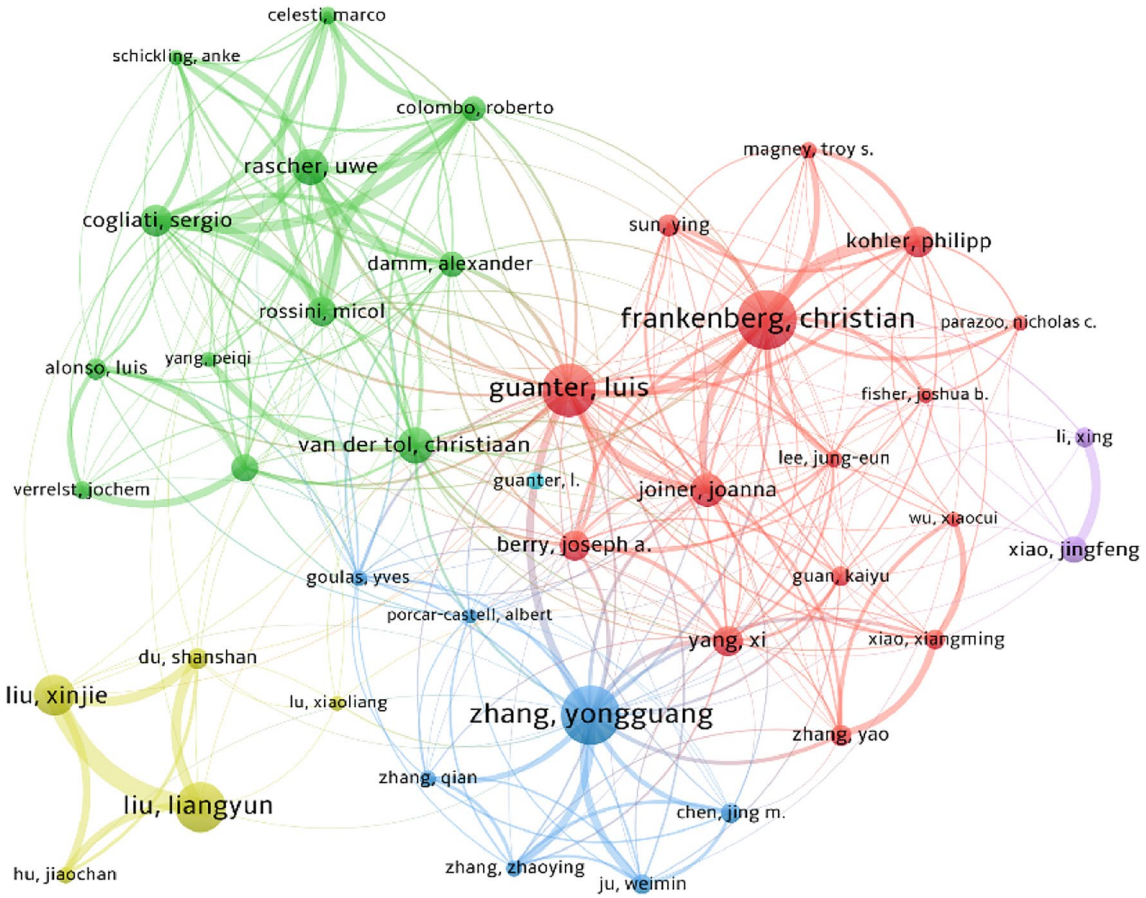

Fig. 5 The cooperation network of authors

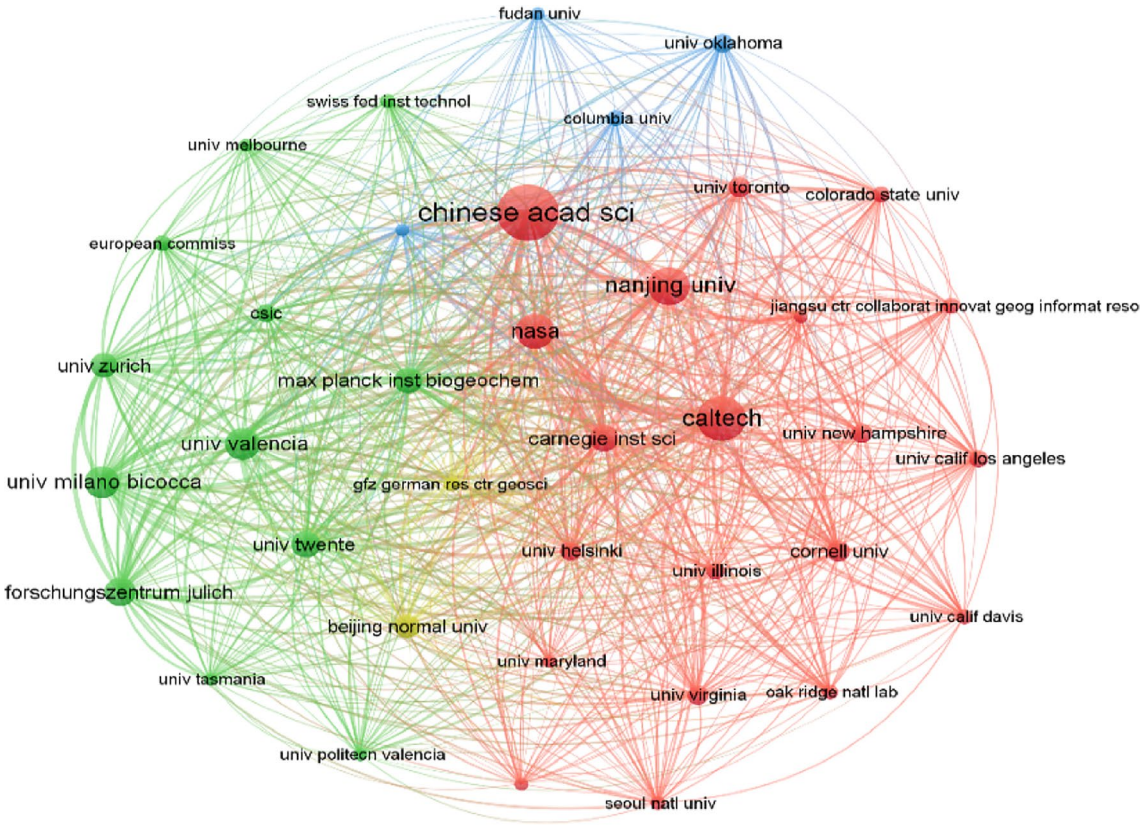

Fig. 6 Mapping of institutions in the SIF research

the top 10 publishing institutions of SIF research are in the Western region, and the other two are from China.

Chinese Acad SCI (92 publications, 20.9%) of the Chinese Academy of Sciences ranked first among all publishing institutions in terms of the number of articles published, followed by Caltech (65 publications, 14.77%), Nanjing University (52 publications, 11.81%), and NASA (44 publications, 10%). However, in terms of average standard citations, although Carnegie Inst SCI and Max Planck Inst biogeochem rank 8th and 10th in the number of published articles, the average standard citations of articles published by these two institutions are indeed the highest, with 2.24 and 1.82, respectively. The quality of research papers published by these two institutions is relatively high. It can be observed from the average year of publication that Chinese Acad SCI has been a relatively active organization in this field in recent years. These analyses generally show that these research institutions have a relatively high level of contribution to the field of SIF research. This information also provides valuable instructions for the recent development research of the institutions and enables scholars to understand the impact and cooperation mode of these studies.

Figure 7 shows the network relationship between authors' organizations. Similarly, the strength of the link depends on the size of the node. According to the parameters set in the "Collaboration: co-author network analyses", a composite network is formed. Institutions with large nodes pay more attention to take more cooperation with other institutions to carry out SIF-related research. The study shows that some institutions in the USA (such as Caltech, NASA, and Carnegie Inst SCI) tend to establish more cooperation with other different institutions. Although Chinese Acad SCI has the largest number of documents in this field, its cooperation with other institutions is not the highest. Although Nanjing University in China has fewer documents than Chinese Acad SCI, it has a higher degree of cooperation with other institutions. Others from Germany, such as Forschungszentrum JULICH, Max Planck Inst biogeochem, University of Toronto from Canada, University of Milano Bicocca from Italy, and University of Twente from the Netherlands, all play an important role in institutional cooperation.

Country co-authorship

In the current study, 44 countries appeared in these 429 publications on SIF research. The USA, China, Germany, Spain, Italy, the Netherlands, France, Australia, Canada, and Switzerland are the top 10 countries with a high output of

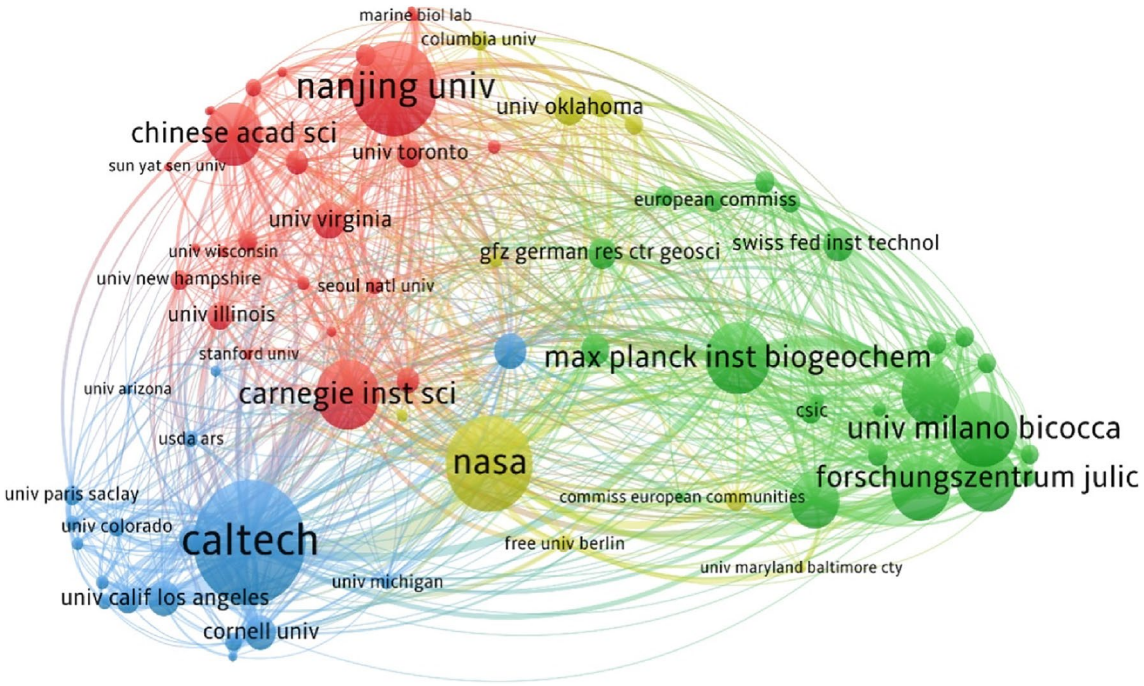

Fig. 7 The cooperation network of institutions

SIF research articles published in the field of remote sensing in the past 17 years (Fig. 8). It can be seen from Table 4 that the number of publications in the USA ranking the first is close to that in China ranking the second, with 204 and 201, respectively, but the number of publications in Germany ranking the third is about half of the top two countries with about 99 publications, and the number of publications in the other countries ranges from 34 to 68 publications. It is worth noting that most of these ten countries are developed countries, except China and Brazil, which are developing countries. Also, only China is located in Asia. Therefore, it can reflect that China has actively established international cooperation in SIF research and increased scientific research on SIF.

The software VOSViewer is used to further study the countries and regions of the selected literature samples and determine the contribution of different countries to the academic community. All 44 countries are included in the compliance network in the analysis (Fig. 9). The network shows the communication and cooperation degree of authors from different countries in SIF research, and the strength of the link depends on the size of the node. Generally, the larger the node, the more cooperation and collaboration between countries and researchers from various countries in SIF research. As shown in Fig. 9 and Table 5, the USA (27 links, 342 total link strength) and Germany (33 links, 314 total link strength), as the two countries with the largest nodes and the most dense links in the national cooperation network, play a key role in this research topic and cooperate closely with other countries. The research results of cooperation among countries also show that the link strength of China (29 links, 241 total link strength) is higher than that of other countries, followed by Spain (30 links, 228 total link strength), Italy (25 links, 212 total link strength), the Netherlands (27 links, 177 total link strength), Switzerland (31 links, 158 total link strength), France (25 links, 145 total link strength), Australia (21 links, 132 total link strength), and Canada (15 links, 101 total link strength). It was found that although Switzerland ranks 10th in the number of publications, its node scale is not the smallest. It can also be seen that countries with a high degree of cooperation on the whole are also countries with a large number of publications. Meanwhile, Germany, Spain, Italy, Netherlands, and New Zealand carried out SIF research relatively early, and the publications are mainly published around 2017, while China and Australia closely followed this trend, especially in 2019, and carried out extensive cooperation with other countries.

Thematic trends and frontier topics: co-occurring keywords

Keyword clustering analysis

Figure 10 shows the keyword clustering relationship. The current research hotspots mainly focus on "validation experiment," "soil moisture," "fluorescence quantum yield," "scope model," "ground chlorophyll fluorescence observation," "vegetation photosynthetic model," "sun-induced

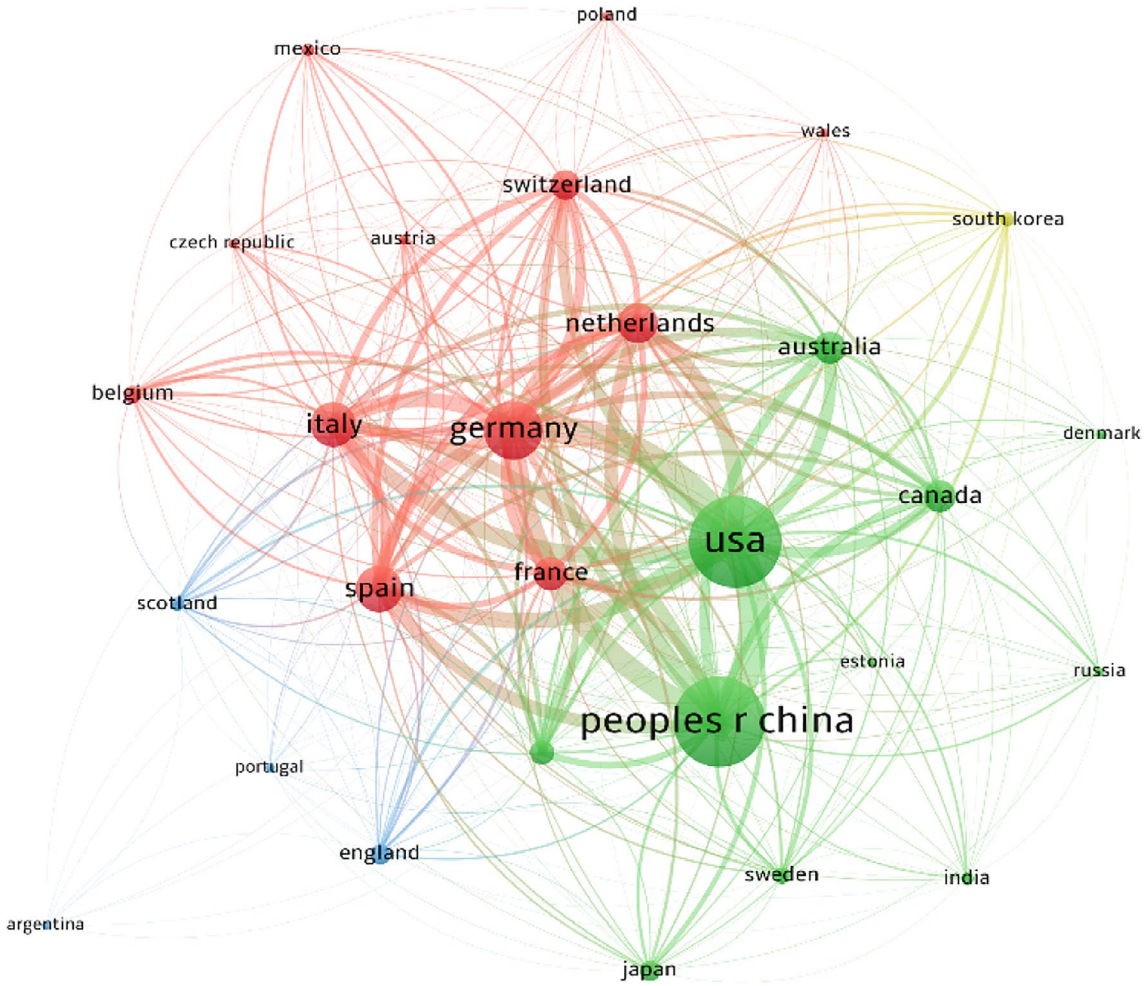

Fig. 8 Visualization of countries in the SIF research

chlorophyll fluorescence," "photochemical reference index," "urbanization," "northern evergreen forest," etc. The first three main research keywords focus on "soil moisture," "fluorescence quantum parameter," and "scope model." At present, the research on soil moisture and quantum yield has always been the hot spot of current research, but in coniferous forest and urbanization, PRI research has become less. Satellite-scale fluorescence and ground-scale fluorescence verification have always been the focus of scholars. Simulation of fluorescence using SCOPE models has been a focus of research in the past few years.

Table 4 Quantitative analysis of influential institutions in SIF research

Organization	Documents	Country	Norm. citations
Chinese acad sci	92	China	72.27
Caltech	65	USA	104.4
Nanjing univ	52	China	60.4
Nasa	44	USA	65.53
Univ Milano Bicocca	39	Italy	41.32
Univ Valencia	39	Spain	48.16
Forschungszentrumjulich	33	Germany	33.39
Carnegie inst sci	30	USA	67.32
Univ twente	30	Netherlands	40.84
Max planckinstbiogeochem	28	Germany	50.94

Research evolution analysis

From 2005 to 2008, keywords mainly focused on photosynthesis, leaf fluorescence, fluorescence model, etc. In this period, papers mainly focused on leaf-scale fluorescence research and achieved a series of research results, for example, the extraction algorithm of leaf fluorescence, the influence of soil moisture on leaf fluorescence, the change of leaf fluorescence under water stress, the change of leaf fluorescence parameters, and so on. From 2009 to 2012, keywords mainly focus on light energy utilization, sun-induced

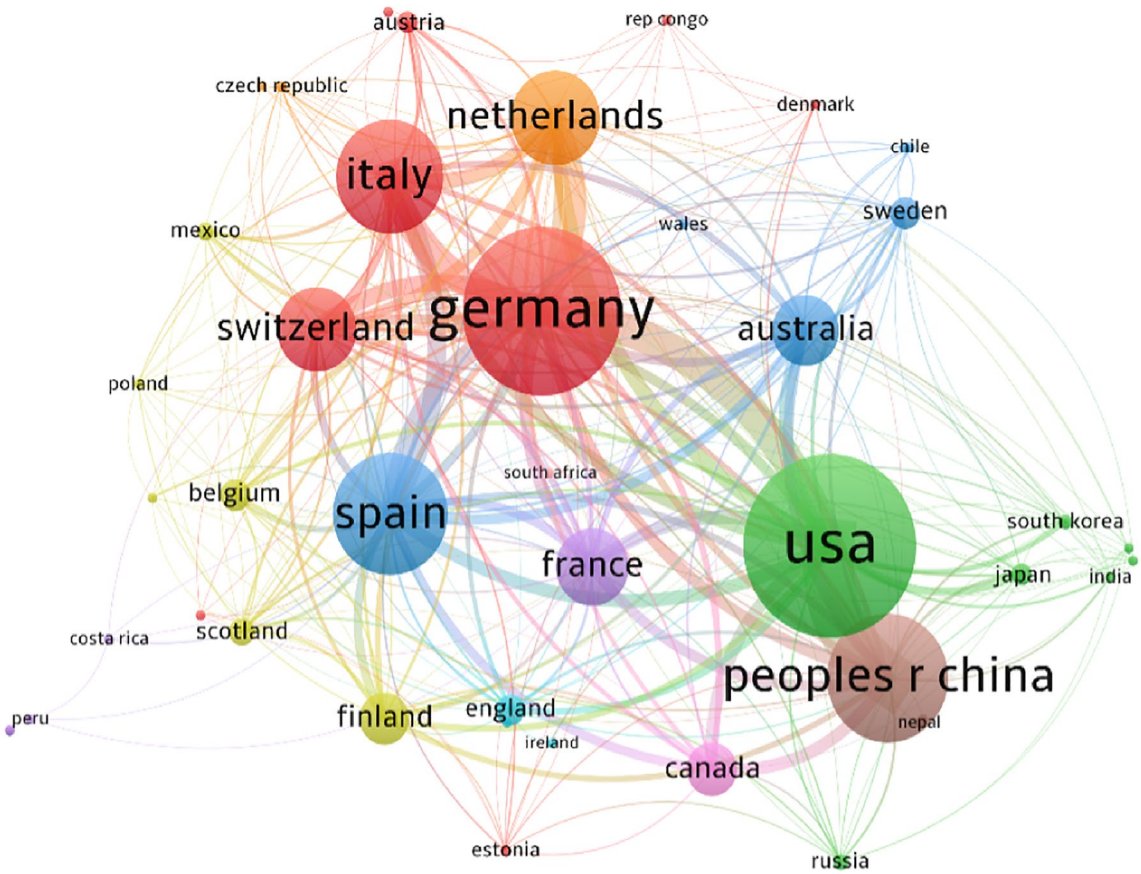

Fig. 9 The cooperation network of countries

chlorophyll fluorescence, CO_2, reflectance, vegetation, etc. (Table 6). From 2013 to 2016, keywords mainly focus on temperature, gross primary productivity, simulation, carbon dioxide, etc. In this period, papers from leaf-scale fluorescence changes to canopy scale fluorescence studies mainly focused on the influence of canopy structure parameters on fluorescence at canopy scale, sun-induced chlorophyll fluorescence canopy extraction, the influence of observation angle on chlorophyll fluorescence, and the regional carbon cycle model driven by canopy fluorescence model. From 2017 to 2021, keywords mainly focus on satellite-scale fluorescence, productivity, mechanism, and climate change (Gitelson et al. 2017; He et al. 2017; Hao et al. 2021).In this period, from the study of canopy scale fluorescence to the study of satellite-scale fluorescence, papers mainly focused on the extraction of sun-induced chlorophyll fluorescence at the satellite scale, the influence of satellite observation angle on chlorophyll fluorescence, and estimated GPP by satellite fluorescence model. The change of keywords of research focus can be seen in Fig. 11. From "leaf scale fluorescence parameters—ground fluorescence—satellite fluorescence—climate change," in the environment of "carbon neutralization and carbon peak," using remote sensing spectroscopy to study climate change is the focus of current research. Photosynthesis, light energy efficiency, GPP, reflectance, vegetation, and temperature are still the most concerned aspects of researchers.

Figure 12 shows the visual change diagram of the keywords clustering timeline in recent 5 years. The maximum

Table 5 Quantitative analysis of article regions in SIF research

Country	Documents	Links	Total link strength
USA	204	27	342
P.R. China	201	29	241
Germany	99	33	314
Spain	68	30	228
Italy	66	25	212
Netherlands	53	27	177
France	40	25	145
Australia	38	21	132
Canada	38	15	101
Switzerland	34	31	158

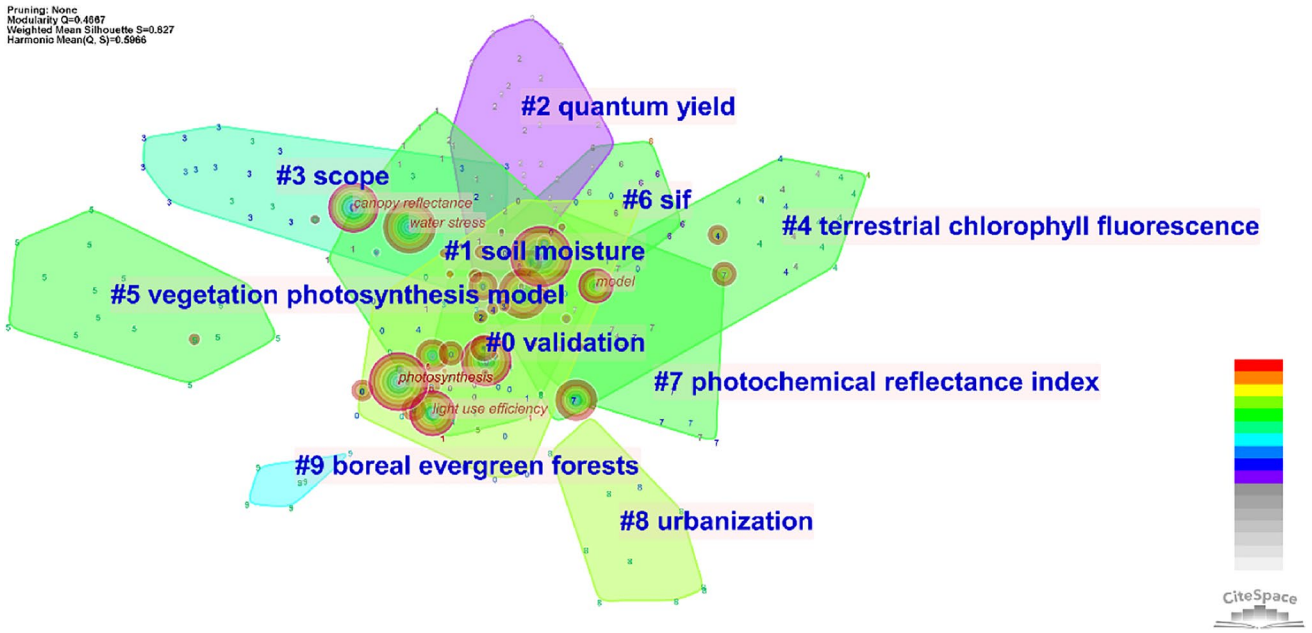

Fig.10 Cluster network in the SIF research

Table 6 Information of keyword clusters

No	Cluster name	Main keywords
0	Validation	validation (8.33, 0.005); canopy structure (7.33, 0.01); temperature (6.82, 0.01); fraunhofer line depth (FLD) (6.68, 0.01); sun-induced chlorophyll fluorescence (6.09, 0.05)
1	Soil moisture	soil moisture (14.61, 0.001); global drought (6.64, 0.01); tibetan plateau (6.64, 0.01); drought monitoring (6.64, 0.01); precipitation (6.64, 0.01)
2	Quantum yield	quantum yield (27.25, 1.0E-4); a fluorescence (18.54, 1.0E-4); phytoplankton (15.06, 0.001); natural fluorescence (15.06, 0.001); algorithm (15.06, 0.001)
3	Scope	scope (9.56, 0.005); scattering (7.83, 0.01); particulate matter (7.56, 0.01); light transfer (5.95, 0.05); remote (5.62, 0.05)
4	Terrestrial chlorophyll fluorescence	terrestrial chlorophyll fluorescence (11.8, 0.001); co2 (11.04, 0.001); sun-induced chlorophyll fluorescence (8.47, 0.005); co2 assimilation (7.86, 0.01); water use efficiency (7.86, 0.01)
5	Vegetation photosynthesis model	vegetation photosynthesis model (VPM) (7.75, 0.01); vpm (7.75, 0.01); nonphotosynthetic vegetation (7.75, 0.01); maize phenology (7.75, 0.01); fluorescence normalization (7.75, 0.01)
6	SIF	SIF (9.29, 0.005); gross primary production (7.42, 0.01); singular value decomposition (SVD) (7.41, 0.01); model (5.43, 0.05); gross primary productivity (4.05, 0.05)
7	Photochemical reflectance index	photochemical reflectance index (10.26, 0.005); PRI (8.24, 0.005); solar-induced chlorophyll fluorescence (SIF) (5.71, 0.05); radiation (5.6, 0.05); spaceborne spectroscopy (4.6, 0.05)
8	Urbanization	urbanization (6.94, 0.01); plant functional types (PFT) (6.94, 0.01); smap (6.94, 0.01); flux-towers (6.94, 0.01); net primary productivity (6.94, 0.01)
9	Boreal evergreen forests	boreal evergreen forests (11.36, 0.001); model GPP (11.36, 0.001); spring recovery (11.36, 0.001); satellite sun-induced chlorophyll fluorescence (11.36, 0.001); vegetation greenness index (11.36, 0.001)

carboxylation rate (V_{cmax}), which determines the photosynthetic capacity of leaves, is a key parameter for estimating the carbon cycle in terrestrial ecosystems, and the relevant research was carried out from 2017 to 2021 (Zheng et al. 2017; Chou et al. 2020). Canopy structure is also an important factor affecting canopy fluorescence and satellite-scale fluorescence extraction. These studies lasted from 2017 to 2020, and attention has decreased in recent years. For example, the canopy structure is the focus of research from 2017 to 2020 (Meroni et al. 2009; Yang and Tol 2018; Chou et al. 2017; Chou et al. 2020). In recent years, China's research focuses on the observation of the dynamics of

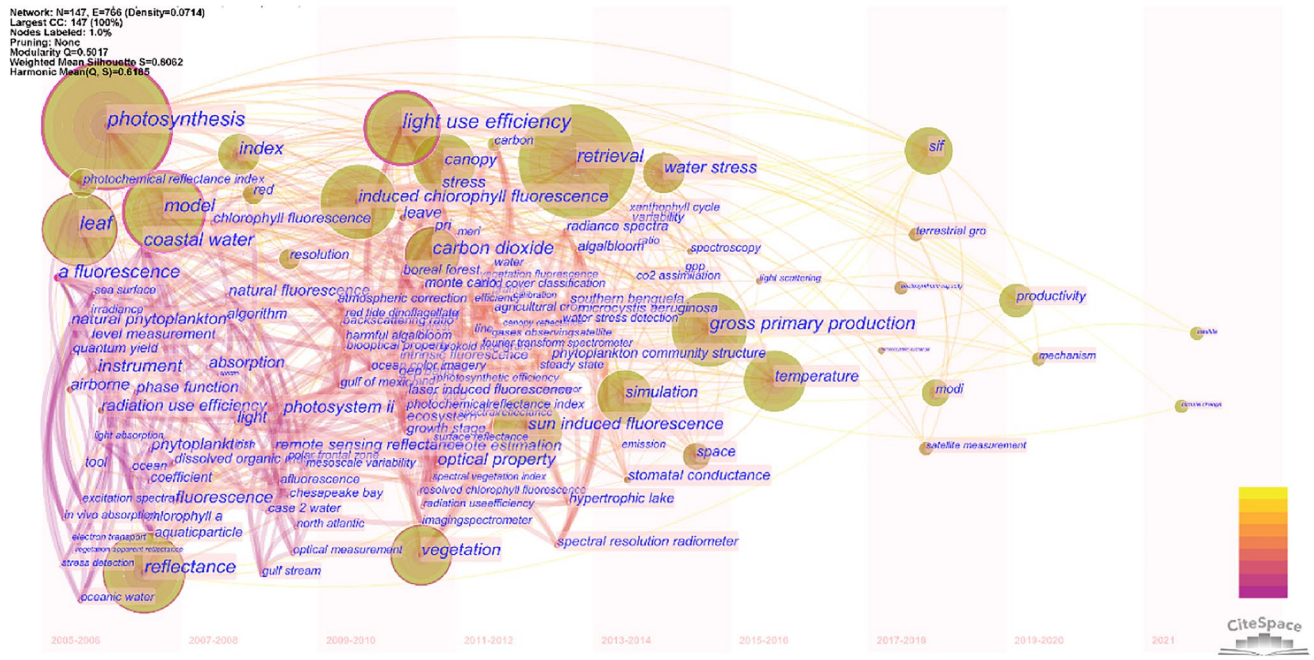

Fig. 11 Keyword co-occurrence time zone view of the development and evolution of SIF, 2005–2021

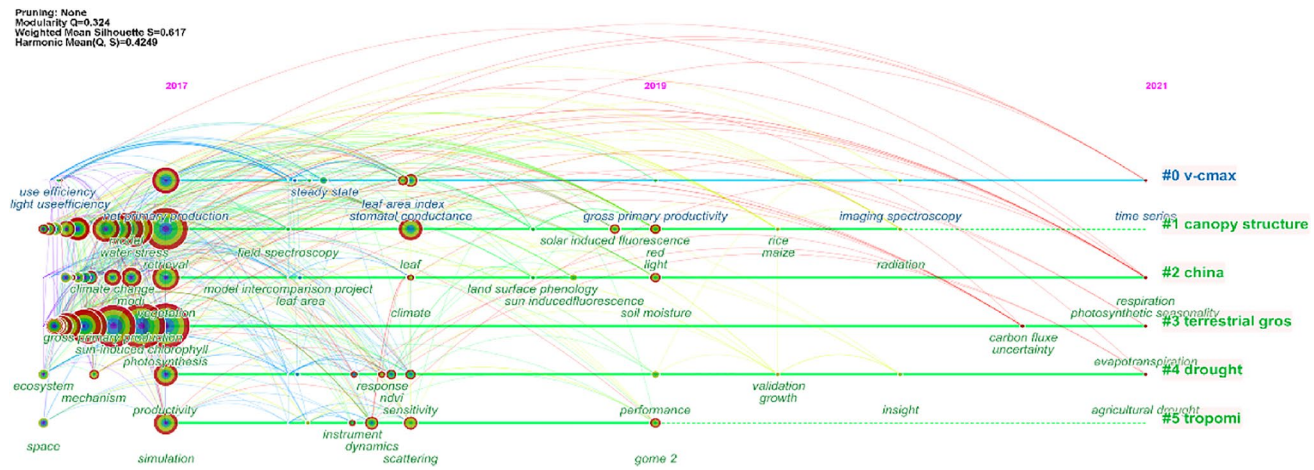

Fig. 12 Timeline of keywords in SIF research area (2017–2021)

sunlight-induced chlorophyll fluorescence on the scale of leaves (Liu et al. 2016, 2017). From 2017 to 2021, ground research is the focus of research. It was the CO_2 inversion in 2018 and the uncertainty of carbon flux research in 2019. Drought research from 2017 to 2021 is the focus of research (Chou et al. 2017; Liu et al. 2017). From 2017 to 2019, "Sentinel-5p" satellite TROPOMI is the focus of research. Sentinel-5P is a global air pollution monitoring satellite launched by the European Space Agency (ESA) on October 13, 2017, with research hotspots from 2017 to 2019, with fewer research papers published after 2019. In the future, some studies will focus on the topic of the leaf parameter (i.e., V_{cmax}, xanthophylls, and chlorophyll). The canopy structure is also a focus of future research. Also, some studies focused more on the uncertainty of carbon flux. These studies can reduce the uncertainty of carbon flux calculations and improve the estimation accuracy of GPP. With the advancement of scientific and technological means, the entire field of research from the blade light energy utilization rate to the canopy scale, to the satellite scale, and then to the study of leaf parameters constantly improves the accuracy of estimating GPP.

As can be seen from the most cited keywords, fluorescence research has gradually shifted from leaf-scale fluorescence parameters, photosystem II and leaf fluorescence parameters, and vegetation reflection direction to PRI, water stress, etc. Studies have mainly focused on the carbon cycle of terrestrial ecosystems and the utilization rate of canopy LUE, and studies on red light fluorescence and fluorescence sensor resolution are the latest key points of attention. From 2012 to 2013, the keywords focus on aviation, vegetation reflectance, and phytoplankton. From 2013 to 2015, the keywords focus on photosystem II and the leaf (Porcar-Castell et al. 2014). The keywords focus on the photochemical reflectance index (PRI) (Cheng et al. 2013; Gitelson et al. 2017; Eitel et al. 2019; Chou et al. 2020), water stress (Zarco-Tejada et al. 2012, 2013; Rossini et al. 2013; Chou et al. 2017), and vegetation fluorescence from 2016 to 2017 (Bagher et al. 2016). Keywords in 2018 focus on space, terrain, and variables. In 2019, the keywords focus on canopy photosynthesis (Croft et al. 2016; Zheng et al. 2017; Croft et al. 2016), red light, and resolution. The keywords gradually changed from "aviation" and "leaf scale fluorescence" to "red fluorescence" and "fluorescence signal extraction from high-resolution remote sensing data" (Fig. 13) (Guanter et al. 2014; Joiner et al. 2016; Liu et al. 2016; Liu et al. 2017; Hao et al. 2021). With the rapid development of information technology, image processing technology, and other related disciplines, the development and application of various types of image sensors are also increasingly flourishing. In recent years, more scholars focus on the extraction of fluorescence signal after the resolution of the sensor is improved.

Conclusions

This scientometric study analyzed the SIF research field, based on publications available in the Web of Science Core Collection database. Visualization and cluster analysis enabled us to map the knowledge domain and intellectual landscape of this field and identify thematic trends, landmark articles, and emerging research themes. The co-authorship analyses at the levels of author, institution, and country revealed the dynamics of research collaborations in the SIF research field. The co-citation analyses identified the documents, journals, and authors, which have had a significant impact. Findings of this study provide an overview of the SIF intellectual base and current research frontiers and highlight the need for generating data appropriate for use in remote sensing of the environment. The relevant conclusions are as follows:

(1) SIF from terrestrial vegetation is a promising optical indicator of photosynthetic status and associated stress effects. Measurement techniques, retrieval algorithms, and modeling of fluorescence-photosynthesis and radiative transfer processes have advanced significantly during the previous few decades. SIF measurements are now made at all biological, geographical, and temporal scales, with exciting application possibilities. To fully fulfill its potential, advancements in all of the topic areas included in this study will be required so that researchers and applied users may confidently apply SIF technology.
(2) SIF is a rapidly developing frontier field in terrestrial vegetation science with emerging space-based technol-

Keywords	Year	Strength	Begin	End	2005 - 2021
airborne	2005	3.04	2005	2012	
vegetation apparent reflectance	2005	2.96	2005	2013	
phytoplankton	2005	3	2006	2013	
photosystem ii	2005	3.36	2008	2017	
leave	2005	3.59	2010	2015	
pri	2005	2.94	2010	2016	
stress	2005	2.89	2010	2015	
vegetation fluorescence	2005	3.97	2011	2016	
space	2005	3.01	2014	2018	
exchange	2005	2.92	2016	2018	
terrestrial gro	2005	4.94	2017	2018	
variability	2005	3.06	2017	2018	
canopy photosynthesis	2005	3.38	2018	2019	
red	2005	5.04	2019	2021	
resolution	2005	3.92	2019	2021	

Fig. 13 Keywords with the strongest citation bursts

ogy capabilities and diversified application prospects. While SIF remote sensing is seen as a novel property for contemporary land plants, it builds on a decade-long history of research, applications, and sensor development for active and passive sensing of chlorophyll fluorescence. As an optical signal, SIF can be remotely evaluated by high-resolution spectral sensors to distinguish emitted from reflected and scattered ambient light. SIF emission from red to far-red light is detectable, and it can be sampled repeatedly to obtain spatiotemporal explicit information about the photosynthetic light response and steady-state behavior of vegetation. With the innovative development of retrieval methods and modeling, the progress of this field is accelerating.

(3) In the past few years, promising developments in the satellite-based detection of SIF have been reported, opening the door to the study of the real photosynthetic process in canopies, ecosystems, landscapes, and biomes in the future, with an emphasis on quantitative accuracy, accessibility to a variety of SIF measures, pertinent supplementary data, and increased spectral, spatial, and temporal resolutions. The maximum carboxylation rate (V_{cmax}), high-resolution spectral sensors, and red SIF have always been a research focus in the future. Also, there will be specialized space-based technologies for SIF in the not-too-distant future, with an emphasis on quantitative accuracy, accessibility to a variety of SIF measures, pertinent supplementary data, and enhanced spectral, spatial, and temporal resolutions.

Author contribution ML: conceptualization, methodology, software, investigation, visualization, and writing—original draft, review, and editing. SC: software, investigation, visualization, funding acquisition, and writing—review and editing. BC: validation, resources, supervision, and writing—review and editing. YW: software and investigation. NL: resources and writing—review and editing.

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Data availability All data generated and analyzed during this study are displayed in the article.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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