

Review

Remote Sensing Applications in Monitoring of Protected Areas: A Bibliometric Analysis

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Abstract: The development of remote sensing platforms and sensors and improvement in science and technology provide crucial support for the monitoring and management of protected areas. This paper presents an analysis of research publications, from a bibliometric perspective, on the remote sensing of protected areas. This analysis is focused on the period from 1991 to 2018. For data, a total of 4546 academic publications were retrieved from the Web of Science database. The VOSviewer software was adopted to evaluate the co-authorships among countries and institutions, as well as the co-occurrences of author keywords. The results indicate an increasing trend of annual publications in the remote sensing of protected areas. This analysis reveals the major topical subjects, leading countries, and most influential institutions around the world that have conducted relevant research in scientific publications; this study also reveals the journals that include the most publications, and the collaborative patterns related to the remote sensing of protected areas. Landsat, MODIS, and LiDAR are among the most commonly used satellites and sensors. Research topics related to protected area monitoring are mainly concentrated on change detection, biodiversity conservation, and climate change impact. This analysis can help researchers and scholars better understand the intellectual structure of the field and identify the future research directions.

Keywords: remote sensing; protected areas; bibliometric analysis; VOSviewer

1. Introduction

In accordance with the International Union for Conservation of Nature (IUCN) [1,2], a protected area (PA) is defined as “a clearly defined geographical space, recognized, dedicated, and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values”. In general, PAs are considered to be areas of land or sea, including national parks, national forests, natural reserves, conservation areas, wilderness areas, marine protected areas (MPAs), and wildlife refuges and sanctuaries, that are designated for the conservation of native biological diversity and natural and cultural heritage and significance [3]. Over the past century, the amount and coverage of both terrestrial and marine PAs have markedly increased [4]. As reported by the World Database on Protected Areas [5], as of July 2018, there were 238,563 designated PAs, covering about 14.9% and 7.3% of the Earth’s land and ocean surface areas, respectively. PAs are central to nature conservation efforts with key environmental, social, cultural and economic functions throughout the world [3,6]. In addition, PAs play an important role in biodiversity conservation and ecosystem integrity [7–10].

Remote sensing refers to the art, science, and technology used for Earth system data acquisition through nonphysical contact sensors or sensor systems mounted on space-borne, airborne, and other types of platforms, data processing and interpretation from automated and visual analysis, information

generation using computerized and conventional mapping facilities, and applications of the generated data and information to benefit society and meet its needs. Remote sensing can provide comprehensive geospatial information to map and study PAs at different spatial scales, e.g., high spatial resolution and large area coverage, different temporal frequencies (e.g., daily, weekly, monthly, or annual observations), different spectral properties (e.g., visible, near infrared, or microwave), and spatial contexts (e.g., the immediately adjacent areas of PAs vs. a broader background of land and water bases). Remote sensing is considered to be a cost-effective method to support the monitoring efforts of PAs and has played a vital role in protecting natural resources, ecosystems, and biodiversity [11,12].

In terms of the large-scale observation ability of remote sensing, the technology is becoming a common practice for monitoring the characteristics and change of land surface properties of PAs [13]. For example, remote sensing has been applied to the assessment of night-time lighting within and surrounding global terrestrial PAs and wilderness areas [14], continuous monitoring of the landscape dynamics of national parks by Landsat-based approaches [15–19], the evaluation of forest dynamics within and around the Olympic National Park using time-series Landsat observations [20], and monitoring the wildlife habitat changes in Kejimikujik National Park and the National Historic Site in southern Nova Scotia of the Canadian Atlantic Coastal Uplands Natural Region [21]. One particular advantage that remote sensing can provide for the inventory and monitoring of protected areas is information to better understand the past and current status, the changes that occurred under different impacting factors and management practices, the trends of changes in comparison with those in the adjacent areas, and the implications of changes on ecosystem functions [22–24]. Remote sensing has unique advantages in monitoring frontier lands, which are always in remote and difficult-to-reach locations and huge in their area coverage. Different types of remote sensing data have been applied in the study of frontier lands—for example, using hyperspectral and radar data to monitor forests in the Amazon [25–30], in Africa [31], and in Siberia [32–35], and for hydrologic change detection in the lake-rich Arctic region [36,37], along the coastal zones [38–41], and in MPAs [42].

There have also been several reviews on PA monitoring using remote sensing. For example, Nagendra et al. [43] provided a review of remote sensing for conservation monitoring by assessing PAs, habitat extent, habitat condition, species diversity, and threats. Kachelriess et al. [44] reviewed the application of remote sensing for MPAs management. Gillespie et al. [45] reviewed advances in the spaceborne remote sensing of terrestrial PAs. Willis [11] provided a review of the remote sensing change detection methods employed for the ecological monitoring of United States PAs. The existing reviews have mainly been focused on a certain type of PAs or the monitoring method. There have been no bibliometric analyses of remote sensing applications in the monitoring of PAs.

Bibliometric analysis, introduced by Pritchard (1969), is a mathematical and statistical approach to analyze pertinent literature and understand the global research trends in a specific area [46,47]. Bibliometric analysis methods are frequently used to provide quantitative analyses of academic literature [48], and have been applied to environmental engineering and science, soil science, ecology, food safety, new energy utilization, and other areas. A bibliometric analysis helps identify research gaps and directions in one certain area [49]. In recent years, studies have applied this method to evaluate the research trends of remote sensing and its application in different scientific fields [50–52]. For instance, Zhang et al. [53] combined the new index (geographical impact factor) and traditional bibliometric methods to study the global research trends in remote sensing studies. Viana et al. [54] performed a bibliometric analysis to appraise the publication, research trends, and characteristics regarding the application of remote sensing data in human health. Wang et al. used the bibliometric method to study the research status and trends in the remote sensing of crop growth monitoring in China [55]. However, no attempt has been made to evaluate the inventory and monitoring of PAs in the literature using bibliometric analysis methods. In recent years, the number of publications on the remote sensing monitoring of PAs has been increasing. Hence, it is necessary to summarize the current status and development trend in this field. With the help of bibliometric methods, researchers can better understand the current number of publications, what journals these documents are published

in, what the influential countries and institutions in this field are, how the research direction of this discipline is developing, etc.

Using a bibliometric approach, this article analyzes the relevant literature specialized in remote sensing applications in PAs. The aims of this work are to (1) summarize the variation in the characteristics of document types, total publication output, subject categories, and source journals; (2) analyze the publication output and international collaboration by countries, institutions, and authors; and (3) reveal the common research topics of PA monitoring research based on a keyword analysis. This research can help us understand the progress in this field and identify the relevant research and application directions.

2. Methodology and Data Collection

The bibliometric indicators analyzed in this research include a number of publications, subject categories, source journals, countries, and institutions, which were all obtained directly from the Web of Science. The Web of Science database can offer various statistics on retrieved papers, including the author, series name, conference name, country/region, document type, editor, fund funding institution, authorization number, group author, language, institution, publication year, research direction, source publication name, and the Web of Science category. Another function of web of science is to “Create a Citation Report”, which can directly generate the total quoted frequency of the retrieved documents, the total quoted frequency of the removed self-cited documents, the quoted documents, the quoted documents of the removed self-cited documents, the average times a document has been cited, and the H-index of each item.

Co-authorship among countries and institutions was also analyzed in this research. Co-authorship mainly analyzes the co-signature of authors in the published paper. If the authors sign their names together in the paper, they are considered to have a cooperative relationship. At present, co-authorship analysis not only focuses on an analysis of researchers, but also includes an analysis of the cooperation between countries and institutions. In the case of the co-authorship analysis, the link strength between countries and institutions indicates the number of publications that two affiliated countries and institutions have co-authored, whereas the total link strength indicates the total strength of the co-authorship links of a given country or institution with other countries and institutions. Similarly, in the case of the co-occurrence analysis, the link strength between the author keywords indicates the number of publications in which two keywords occur together. In order to investigate the development of remote sensing in the field of protection area monitoring, we determined the keywords related to satellite, sensor and remote sensing monitoring method from the results of the co-occurrence keywords.

In this study, the VOSviewer software was utilized to visualize the co-authorship collaboration networks of countries and institutions and produce a keywords co-occurrence analysis. Invented by Van Eck and Waltman (Leiden University) in the Netherlands, VOSviewer is freely available -text mining software for generating bibliometric maps and analyzing trends in the scientific literature [56]. The outstanding feature of VOSviewer is its strong graphic display ability, which is especially suitable for analyzing large-scale sample data. This visualization effect is better than that of other similar analysis software, and the analysis function is more comprehensive. VOSviewer is a robust tool that uses clustering algorithms and functionalities based on the strength of the connections among items to facilitate the analyses of the network. [57]. The VOSviewer software uses a circle and label to represent an element, in which the circle size represents the importance, and circles with the same color belong to the same cluster.

Bibliometric maps are created by VOSviewer. These maps include items such as countries, institutions, and author keywords in the present study. The connection or relation between two items is named a link. The strength of a link indicates the number of publications that two countries or institutions have co-authored in the case of co-authorship links, or the number of publications in which two author keywords occur together in the case of co-occurrence links [46,58]. In the VOSviewer, there are two methods used to calculate link strength: full counting and fractional counting.

Full counting means that a co-authored publication is counted with a full weight of one for each co-author, which implies that the overall weight of a publication is equal to the number of authors of the publication. Fractional counting means that a co-authored publication is assigned fractionally to each of the coauthors, with the overall weight of the publication being equal to one. As analyzed by Perianes-Rodriguez et al. (2016), a fractional counting approach is preferable to full counting [59]. Therefore, we chose fractional counting to calculate the link strength.

VOSviewer uses a clustering algorithm to cluster the literature network, which is similar to the network clustering method of Modularity, specifically the maximization formula:

$$V(c_1, \dots, c_n) = \frac{1}{2m} \sum_{i < j} \delta(c_i, c_j) w_{ij} \left(c_{ij} - \gamma \frac{c_i c_j}{2m} \right) \quad (1)$$

$$w_{ij} = \frac{2m}{c_i} c_j \quad (2)$$

where c_i is the cluster of element I , and γ is the resolution of clustering. By adjusting its size, different resolution clustering can be obtained. The larger γ is, the more clustering will be obtained, and the finer the classification will be.

In VOSviewer, the number of clusters is determined by the option “choose threshold”. In the case of a co-authorship analysis, the threshold is the minimum number of documents of a country or an institution. In the case of co-occurrence analysis, the threshold is the minimum number of occurrences of a keyword. We can choose the threshold according to our own needs.

The VOSviewer software has been widely used in bibliometric analyses in many fields. For example, Santos et al. used VOSviewer to map knowledge networks on female entrepreneurship [60]. Sainaghi et al. mapped the co-citation network of journals and authors on the foundations of hospitality performance measurement research using VOSviewer [61]. Sweileh et al. used VOSviewer to visualize map-based bibliometric indicators for the global research output on antimicrobial resistance among uropathogens [62].

The relevant documents were retrieved from the Science Citation Index Expanded (SCI-Expanded) and Social Science Citation Index (SSCI) of the Web of Science database, which is a multidisciplinary database of Thomson Reuters [63]. The following keywords were used to search all archived documents: TS (Topic) = “protected area*” or “natural reserve*” or “conservation area*” or “national park*” or “national forest*” or “marine protected area*” or “wilderness area*” or “frontier land*” or “natural monument*” or “biodiversity conservation” and “remote sensing”. The publications that contained any of those keywords or variants (with*) in their titles, abstracts, and keyword lists were included [48]. The information on title, authors, institution, abstract, keywords, and cited references was downloaded. We set the starting time of this study as 1991, considering that the number of publications under the subject of remote sensing applications in PAs and relevant studies increased significantly after 1991 in professional journals and publications. This is illustrated in Figure 1. The data collection was conducted on 16 November 2019. Until 2018, a total of 4546 records were retrieved as the data for this analysis. Among these records, 3994 papers were focused on the remote sensing monitoring of terrestrial PAs, while the other 552 papers were on MPAs.

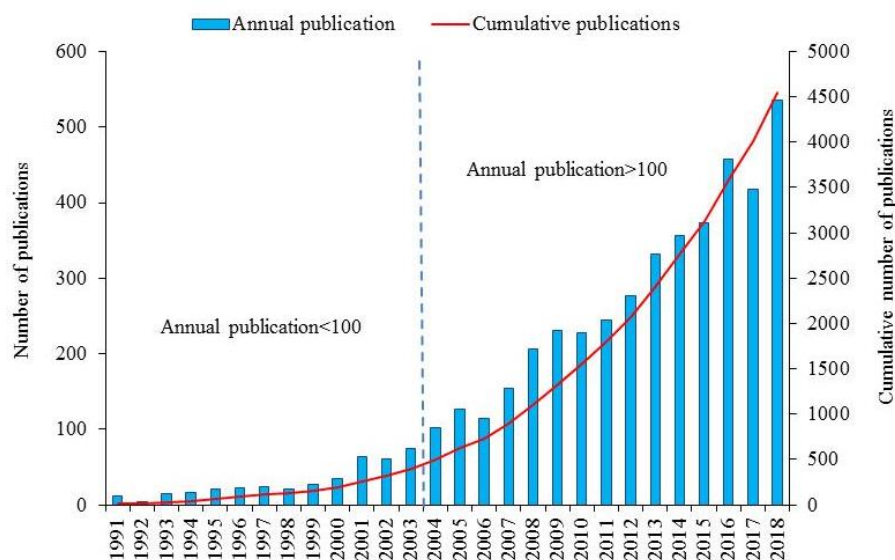


Figure 1. Annual publication and cumulative number, 1991–2018.

3. Results

3.1. General Characteristics and Trends of Publication Outputs

The trend for publications from 1991 to 2018 is illustrated in Figure 1. In general, the number of publications has shown an increasing trend over the years, with small fluctuations between individual years. According to the dates, the evolution of the published article output can be divided into three stages. The first stage extends from 1991 to 2003, with a relatively slow growth period. The second stage features a steady growth period from 2004 to 2011. The third stage is a fast growth period from 2012 to 2018.

The sample documents covered a total of 108 subject categories. The research domain covered a wide variety of themes and disciplines. The top 10 subject categories with more than 200 documents are displayed in Figure 2. The results indicate that environmental sciences ranked first with 1524 publications, followed by remote sensing with 1062 publications, ecology with 946 publications, and imaging science and photographic technology with 652 publications. Multidisciplinary geosciences, physical geography, forestry, biodiversity conservation, water resources, and meteorological and atmospheric sciences were also relevant subject categories.

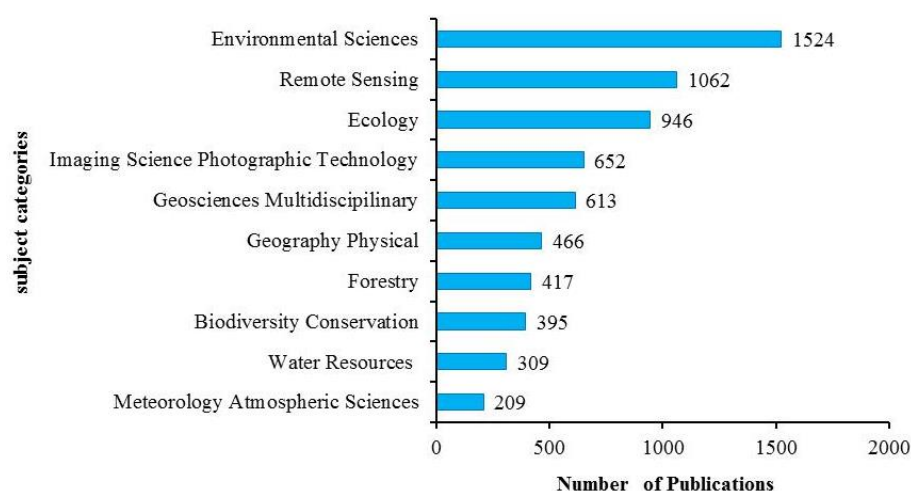


Figure 2. Top 10 subject categories in the field of the remote sensing monitoring of protected areas (PAs).

For the source journals, 739 different journals published papers related to remote sensing for PA monitoring. Table 1 shows the top 20 journals in terms of total relevant publications. Remote Sensing of Environment ranked first, with 256 articles covering 5.63% of the total publications. Remote Sensing ranked second, with 174 articles accounting for 3.83%, while the International Journal of Remote Sensing ranked third, with 153 articles accounting for 3.37%. The ISPRS Journal of Photogrammetry and Remote Sensing, Forest Ecology and Management, and the International Journal of Applied Earth Observation and Geoinformation (ranked 4th, 5th, and 6th places) accounted for 2.38%, 2.11%, and 2.02%, respectively.

Table 1. Top 20 main source journals in the research field.

Rank	Name	Country	Number	Percentage%
1	Remote Sensing of Environment	USA	256	5.63
2	Remote Sensing	Switzerland	174	3.83
3	International Journal of Remote Sensing	UK	153	3.37
4	ISPRS Journal of Photogrammetry and Remote Sensing	Netherlands	108	2.38
5	Forest Ecology and Management	Netherlands	96	2.11
6	International Journal of Applied Earth Observation and Geoinformation	Netherlands	92	2.02
7	Ecological Indicators	Netherlands	78	1.72
8	Environmental Monitoring and Assessment	Netherlands	70	1.54
9	Biological Conservation	UK	69	1.52
10	Applied Geography	UK	62	1.36
11	PLOS One	USA	58	1.28
12	Ecological Applications	USA	53	1.17
13	Journal of the Indian Society of Remote Sensing	USA	47	1.03
14	International Journal of Wildland Fire	Australia	44	0.97
15	Current Science	India	43	0.95
16	Environmental Management	USA	43	0.95
17	Environmental Research Letters	UK	43	0.95
18	Journal of Environmental Management	UK	42	0.92
19	Landscape Ecology	Netherlands	42	0.92
20	Biodiversity and Conservation	Netherlands	39	0.86

3.2. Countries, Institutions, and International Collaboration

According to the retrieved results, the papers covered a total of 153 different countries (or territories, hereafter referred to as “countries” for simplification). The geographical distribution of the top 20 productive countries for the overall study period is shown in Figure 3. The USA ranked first with a dominant output of 1655 papers or a share of 36.41%. China had 619 papers (13.62%) and UK had 479 (10.54%), ranking second and third, respectively. Other top ranked countries are Germany (7.92%), India (7.90%), Australia (7.11%), Canada (6.64%), and Italy (5.65%).

The co-authorship analysis studied a network of the main countries, which is plotted in Figure 4. These countries published more than 60 papers. There were four main clusters formed in the network (Table 2). The USA showed 62,644 citations and a link strength of 634, the UK showed 14,335 citations with a link strength of 241, and China showed 12,906 citations with a link strength of 265, which surpassed all the other clusters. The strongest link strength was evidenced by the USA and China, with a 151.93 link strength, followed by the USA and Canada with a 64.89 link strength, the USA and the UK with a 58.69 link strength, the USA and Germany with a 49.93 link strength, the USA and Australia with a 46.48 link strength, and the USA and Brazil with a 43.59 link strength.

According to the results, 4451 institutions contributed to the analyzed publications. The top 15 research institutions with the largest number of documents are listed in Table 3. By far the most productive institution was the Chinese Academy of Sciences in China, with 296 publications. The University of Maryland was in second place with 118 publications. The Chinese Academy of Sciences also ranked first in number of citations, followed by NASA, University of Maryland, and the U.S. Forest Service.

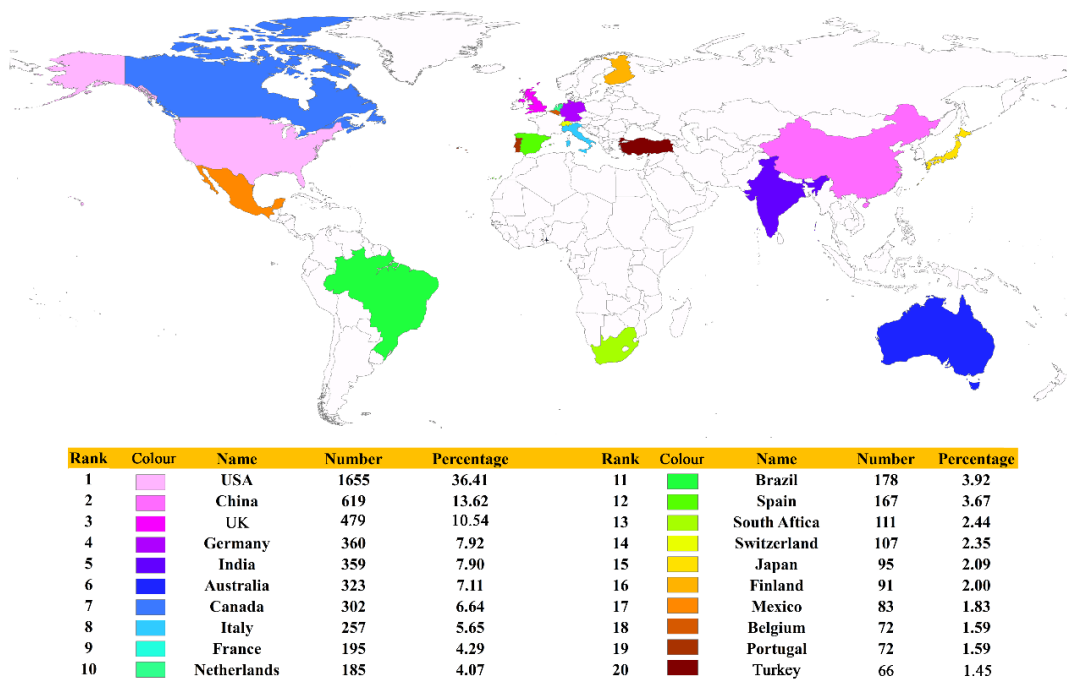


Figure 3. The geographic distribution of the top 20 productive countries.

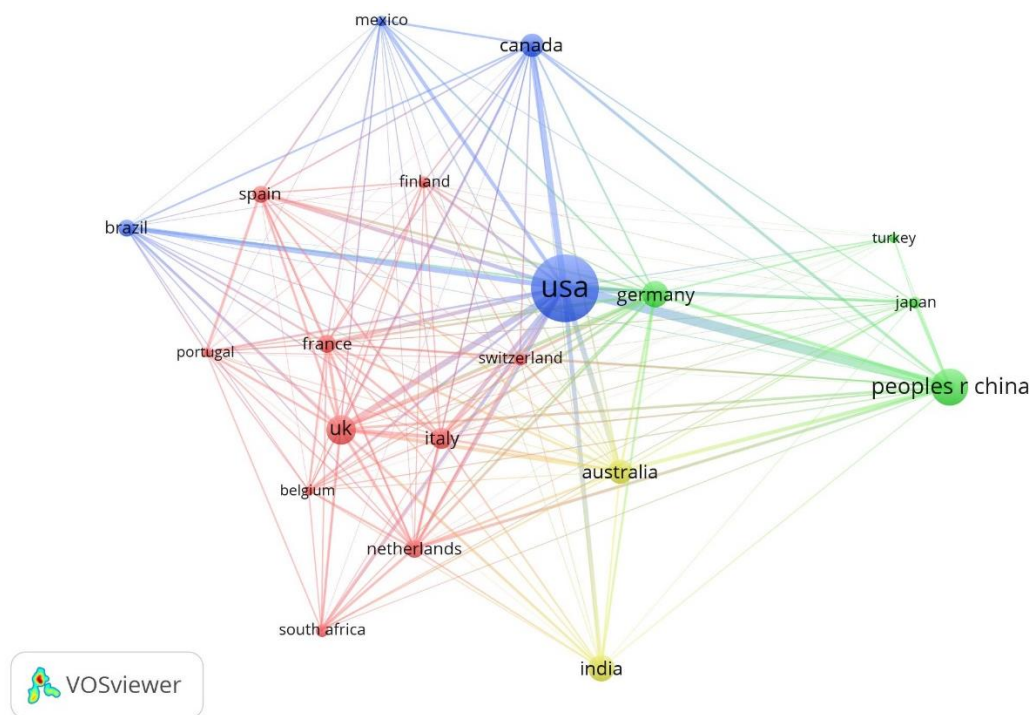


Figure 4. Co-authorship cooperation between productive countries. Each node represents a country. The size of the nodes reveals the citations of the countries, while the thickness of the lines between them shows the strength of collaboration.

Table 2. 5 main clusters for country collaboration.

Cluster	Country	Citations	Link Strength
1	UK	14,335	241
	Italy	8924	133
	Netherlands	7298	128
	France	6838	124
	Spain	4732	96
	Switzerland	4361	70
	South Africa	2715	59
	Finland	2596	40
	Belgium	1980	50
	Portugal	1288	54
2	USA	62,644	634
	Canada	11,665	140
	Brazil	4926	94
	Mexico	2026	58
3	China	12,906	265
	Germany	11,147	200
	Japan	2562	45
	Turkey	513	8
4	Australia	10031	164
	India	6772	73

Table 3. Top 15 institutions based on total publications.

Rank	Organization	Country	Number	Percentage %	Citations
1	Chinese Academy of Sciences	China	296	6.51	7279
2	University of Maryland	USA	118	2.60	5683
3	U.S. Forest Service	USA	110	2.42	5376
4	NASA	USA	108	2.38	6668
5	U.S. Geological Survey	USA	84	1.85	2842
6	University of Chinese Academy of Sciences	China	63	1.39	1222
7	Beijing Normal University	China	61	1.34	1703
8	University of Queensland	Australia	59	1.30	2347
9	University of Wisconsin	USA	56	1.23	3535
10	Oregon State University	USA	54	1.19	2367
11	University of Florida	USA	53	1.17	1529
12	Caltech	USA	51	1.12	2086
13	University of British Columbia	Canada	51	1.12	2765
14	University of Oxford	UK	48	1.06	1381
15	Natural Resources Canada	Canada	47	1.03	1636

An institutional cooperation network based on the VOSviewer software for the construction of scientific maps is presented in Figure 5. This figure presents the four clusters of collaboration among the prolific institutions with 35 or more publications. The largest cluster (red) contains nine institutions. All the institutions in the red cluster belong to the USA. The green and blue clusters both contain five institutions. Two of the institutions in the green cluster belong to the Netherlands, and the remaining three are from Australia, the UK and the USA. The blue cluster is composed of three Chinese institutions and two American institutions. The fourth cluster (yellow) includes three institutions from Canada. It can be seen that the cooperation between institutions is mainly focused within the same country or neighboring countries.

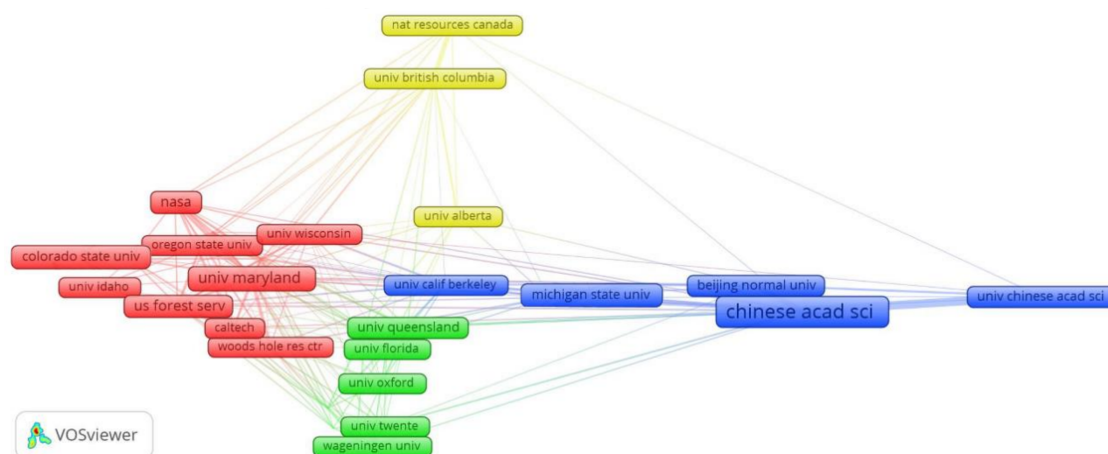


Figure 5. Co-authorship cooperation between productive institutions. The colors represent clusters of institutions, the size of frames represents the number of articles published by these institutions, and the lines represent the strength of cooperation among institutions.

3.3. Common Interests in Research Topics

Keywords, a core element of papers, offer a highly summarized form of a paper's contents. In order to understand the focus areas and development trends of one field, it is necessary to systematically analyze the selection of keywords in relevant studies [64]. Table 4 shows the 20 most frequently used author keywords from 1991 to 2018, including "remote sensing", "GIS", "Landsat", "deforestation", "LiDAR", "conservation", and "biodiversity", for research on PA monitoring that is concentrated on deforestation and biodiversity conservation.

A statistical analysis of the changes in the author keywords between different stages is beneficial for a comparative analysis of the changes in common research subjects and the development process of PA monitoring studies [19,65,66]. Table 4 separates the development of PA monitoring research into three stages, namely 1991–2003, 2004–2011, and 2012–2018. "Remote sensing" and "Landsat" were the most frequently used author keywords and appeared in the top 20 in all three periods. The "MODIS" and "LiDAR" keywords increased in frequency of appearance from 1991 to 2011 and increased further in 2012–2018, which indicates that the platform played a significant important role in PA monitoring. Comparing the three different stages, the keywords rankings changed considerably. The keyword "climate change" began to appear in the top 10 during 2012–2018, which suggests that more attention was being given to climate change on PA research. The research focus of each stage is as follows. The early stage of research focuses on landscape ecological change and human disturbance. The middle stage focuses on the change detection of land cover and land use caused by deforestation. The late stage focuses on the impact of climate change on PAs.

In order to trace the trend of the remote sensing data used in PAs research, the most frequently selected keywords related to satellites and sensors were counted. The top ten are Landsat, MODIS, LiDAR, SPOT, AVHRR, ASTER, IKONOS, PALSAR, Sentinel (Sentinel-1 and Sentinel-2), and WorldView, with low, moderate, or high-resolution sensors. The annual publications of the top ten satellites and sensors are shown in Figure 6. In terms of quantity, Landsat was the most frequently used satellites and sensors type, with 1078 papers, followed by MODIS with 439 papers and LiDAR, with 370 papers. In addition, with the continuous development of remote sensing technology, some new platforms and satellites have emerged and have been applied to monitor PAs in recent years. For example, there were 35 papers on the UAV monitoring of PA, and 26 papers on small satellites from 2001 to 2008.

Table 4. Top 20 author keywords in different stages, 1991–2018, 1991–2003, 2004–2011, and 2012–2018. F(%)—frequency of author keywords and their percentage of total publications in the corresponding stage. The total publications numbered 4546 in 1991–2018, 393 in 1991–2003, 1405 in 2004–2011, and 2748 in 2012–2018.

Rank	1991–2018		1991–2003		2004–2011		2012–2018	
	Keywords	F (%)	Keywords	F (%)	Keywords	F (%)	Keywords	F (%)
1	remote sensing	1933 (42.52)	remote sensing	135 (34.35)	remote sensing	659 (46.90)	remote sensing	1139 (41.45)
2	Landsat	1078 (23.71)	Landsat	112 (28.50)	Landsat	353 (25.12)	Landsat	613 (22.31)
3	MODIS	439 (9.66)	GIS	48 (12.21)	GIS	159 (11.32)	MODIS	310 (11.28)
4	GIS	425 (9.35)	landscape ecology	12 (3.05)	MODIS	118 (8.40)	LiDAR	293 (10.66)
5	LiDAR	370 (8.14)	MODIS	11 (2.80)	LiDAR	72 (5.12)	GIS	218 (7.93)
6	deforestation	161 (3.54)	conservation	11 (2.80)	biodiversity	49 (3.49)	deforestation	115 (4.18)
7	conservation	146 (3.21)	biodiversity	9 (2.29)	NDVI	42 (2.99)	conservation	97 (3.53)
8	biodiversity	136 (2.99)	modeling	8 (2.04)	deforestation	39 (2.78)	biodiversity	78 (2.84)
9	NDVI	124 (2.73)	land-cover	8 (2.04)	conservation	38 (2.70)	climate change	78 (2.84)
10	protected area	106 (2.33)	deforestation	7 (1.78)	protected area	36 (2.56)	NDVI	78 (2.84)
11	land-use	105 (2.31)	fragmentation	7 (1.78)	land-cover	34 (2.42)	protected area	68 (2.47)
12	land-cover	104 (2.29)	land-use	7 (1.78)	land-use	32 (2.28)	land-use	66 (2.40)
13	climate change	99 (2.18)	disturbance	6 (1.53)	wetland	32 (2.28)	land-cover	62 (2.26)
14	change detection	95 (2.09)	mapping	6 (1.53)	change detection	31 (2.21)	change detection	60 (2.18)
15	wetland	87 (1.91)	forest	6 (1.53)	tropical forest	29 (2.06)	land-use change	59 (2.15)
16	land-use change	83 (1.83)	LiDAR	5 (1.27)	land-cover change	29 (2.06)	wetland	54 (1.97)
17	monitoring	82 (1.80)	habitat fragmentation	5 (1.27)	monitoring	28 (1.99)	random forest	52 (1.89)
18	land-cover change	77 (1.69)	fire	5 (1.27)	land-use change	23 (1.64)	ecosystem service	52 (1.89)
19	forest	68 (1.50)	classification	5 (1.27)	forest	22 (1.57)	monitoring	51 (1.86)
20	soil erosion	62 (1.36)	satellite remote sensing	5 (1.27)	hyperspectral	22 (1.57)	REDD	44 (1.60)

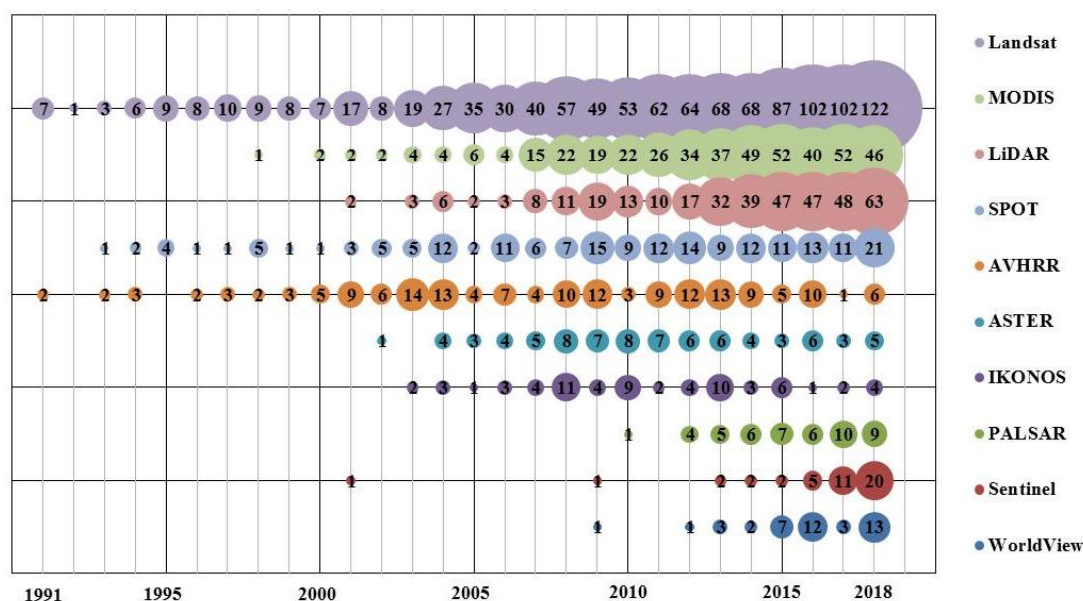


Figure 6. Annual publications of the main satellites and sensors in the research field.

Based on the co-occurrence analysis, the remote sensing monitoring methods are also counted in Table 5. The remote sensing monitoring methods mainly include classification, time-series analysis, model methods, object-oriented method, visual analysis, direct comparisons, and hybrid methods [67,68]. The classification method holds the first position with 526 papers and 11.57% of the total publications, followed by time-series analysis (288, 6.34%) and model method (159, 3.50%).

Table 5. The main remote sensing monitoring methods used for protected areas (PAs).

Rank	Methods	Number	Percentage %
1	classification	526	11.57
2	time-series analysis	288	6.34
3	model method	159	3.50
4	object-oriented method	131	2.88
5	visual analysis	95	2.09
6	direct comparison	72	1.58
7	hybrid methods	57	1.25

Figure 7 shows a co-occurrence network analysis of the keywords, which can be used to identify the research front in terms of topical trends for PA monitoring. In this analysis, the minimum number of occurrences of a keyword is 30 times for titles and abstracts in all publications. The research theme of PA monitoring has been categorized into six colored clusters, which were analyzed as follows. The red cluster with the highest number of keywords (12) is led by “land cover”; In addition, “land use”, “monitoring”, “mapping”, “hyperspectral”, and “classification” are also the main keywords of this cluster. Most keywords in this cluster are associated with studies on land use and land cover classification using hyperspectral remote sensing data. The blue cluster, with 11 keywords, has “Landsat”, “MODIS”, “NDVI”, “climate change”, “change detection”, and “wetland” as its main related keywords, which appear in the relevant research on the habitat mapping and change detection of PAs, as well as the impact of climate change. The green cluster (11 keywords) focuses on the keywords: “deforestation”, “LiDAR”, “REDD”, “biomass”, “forest inventory”, “tropical forest”, “forest management”, and “carbon”. The keywords of this cluster are closely related to estimating forest biomass and carbon storage in PAs using LiDAR data. The yellow cluster has 10 keywords; the most frequently used is “remote sensing” followed by “conservation”, while “biodiversity”, “protected areas”, and “fragmentation” are ranked 3rd–5th, respectively. Most keywords in this cluster relate to

the use of remote sensing to support biodiversity conservation in PAs. The number of keywords in the purple cluster is four, including “land-use change”, “land-cover change”, “ecosystem service”, and “landscape metrics”. This cluster is related to the analysis of land-use/land-cover change and ecosystem service evaluation by remote sensing and landscape metrics. The orange cluster includes only three keywords. The keyword “GIS” appears most frequently, with a total of 387 occurrences. The other two keywords are “soil erosion” and “RUSLE (The Revised Soil Loss Equation)”. This cluster has connections with keywords related to the study of soil erosion and its spatial distribution in PAs using the GIS analysis method.

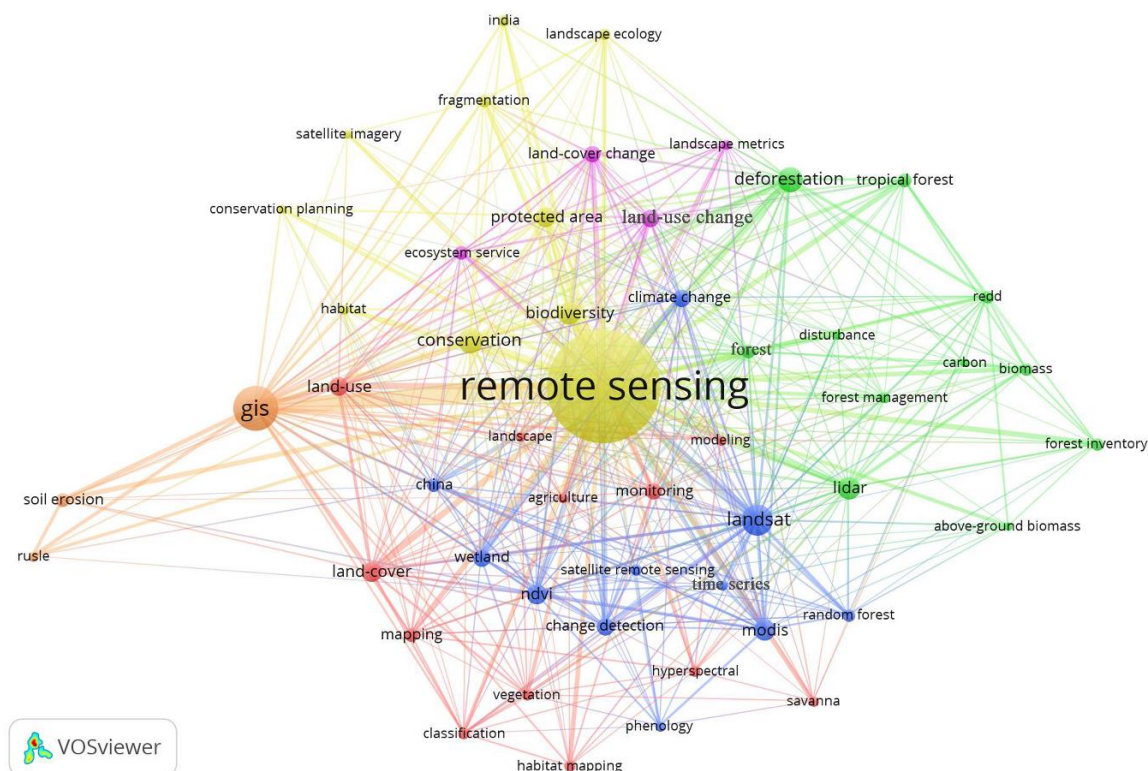


Figure 7. Keywords co-occurrence network. Each node represents a keyword, the size of the node indicates the number of occurrences of the keyword, and the line thickness of the two nodes represents the degree of connection.

4. Discussion

In this paper, by retrieving the relevant literature on remote sensing monitoring protected areas, we revealed hidden knowledge underlying this significant body of research. The number of publications shows a trend of continuous growth, demonstrating that more and more scholars have paid attention to this research field. From the perspective of subject categories, environmental sciences ranked first, followed by remote sensing and ecology, which shows that the remote sensing monitoring of PAs is a field closely related to environmental science, remote sensing, and ecology. The top three journals are all well-known journals in the field of remote sensing, include Remote Sensing of Environment, the International Journal of Remote Sensing, and the ISPRS Journal of Photogrammetry and Remote Sensing.

For country of origin, the USA is in the leading position. Moreover, the top 20 countries are mostly European countries. When considering institutions, the Chinese Academy of Sciences published the largest number of papers. The United States has the largest number of research institutions in the top 15, accounting for more than half of them. Through the co-authorship analysis of countries and institutions, this study determined that the USA was at the center of international cooperation,

and the cooperation among national research institutions was relatively close, while its international cooperation was relatively less prevalent, which is not conducive to the long-term development of remote sensing monitoring for PAs. Countries and institutions should strengthen their knowledge exchanges and cooperation to more effectively discuss research trends and research status in the research field by holding relevant academic forums and conferences.

The analysis results showed that studies have mainly concentrated on terrestrial PAs, while literature on MPA monitoring is relatively less common. Future research should make full use of new monitoring technology and methods to establish a long-term, scientific, and systematic monitoring system and thereby provide a data-based foundation for evaluating the effectiveness of MPAs. Based on the changes in keywords, it can be seen that remote sensing monitoring of PAs mainly focused on vegetation classification, landscape pattern analysis, biodiversity protection, and the monitoring of changes in PAs. Future research trends will focus on the impact of climate change on PAs.

Considering temporal variation, the use of Landsat, MODIS, and LiDAR show a clear fluctuating and increasing trend. LiDAR and SAR have been increasingly used to monitor and evaluate the landscape in recent years. Different satellites and sensors are now applied in different fields and at different scales of PAs. For example, Landsat products include the Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), and Operational Land Imager (OLI), which can be used to monitor vegetation dynamics and assess land-cover/land-use change. However, MODIS sensors are more appropriate for vegetation phenology and forest fire monitoring and can provide high temporal resolution time series data at the landscape, regional, and global spatial scales. LiDAR makes it possible to estimate tree height, biomass, and leaf area index in large areas of the world [69,70]. SAR facilitates the estimation of forest biomass and tree height at small and medium scale [71]. Furthermore, SPOT or QuickBird may be used for species or specific vegetation change monitoring [72–74]. AVHRR sensors are mainly used to analyze the impact of climate change on vegetation coverage in PAs. The high spatial resolution of ASTER can also be used to study land-cover/land-use change in PAs [75]. Other high-resolution satellites, such as IKONOS and WorldView, focus on mapping vegetation types or habitat associated with endangered fauna [76,77].

In recent years, with the rapid development of satellites, sensors, and techniques, the applications of remote sensing have been broadly employed in the monitoring and management of PAs. The relevant research results for improving the level of monitoring in PAs, formulating differentiated regional protection policies, and guiding sustainable development play an important role. According to this bibliometric analysis, research on the remote sensing monitoring of PAs has mainly focused on the inventory and classification of vegetation, change detection, habitat degradation, the impact of climate change, and biodiversity conservation. Among the various methods, classification, time series analysis, and model methods were the most frequently used types for PA monitoring. In the foreseeable future, there will be more new methods to monitor PAs. For example, big data approaches are being adopted to process large amounts of remote sensing data [78–80].

There are still some limitations to this study. Firstly, the single database that we used does not index all scientific journals and theme books, which could exclude some relevant articles. For example, some gray literature on this topic from government agencies, nature conservancies and other non-profits might have been excluded. Expanding the search across multiple databases, such as Scopus and Google Scholar, will help reduce omissions in the analysis. Secondly, setting 1991 as the starting time may omit some earlier studies. However, most articles relevant to remote sensing applications in PAs were published in professional journals from 1991 onwards. Therefore, we believe that using 1991 as the starting point is still representative and appropriate. Thirdly, the VOSviewer software has some functional restrictions. Another consideration is that other bibliometric analysis tools, such as Citespace, could be applied in combination with VOSviewer in the future to more extensively cover the published research on the remote sensing of PAs. In the meantime, we acknowledge that it is almost impossible to include all remote sensing applications for PAs by limiting the search to include “remote sensing” alone. Other terms and descriptions, such as “land-cover monitoring”, “landscape configuration and

composition”, “habitat analysis”, “biodiversity conservation”, and “bathymetry assessment”, among other examples, could be very relevant to studies in protected areas with remote sensing applications, but could be missed in the analysis. This is particularly true for monitoring changing terrestrial and marine environments under impacts from the natural and anthropogenic disturbances of protected areas. This challenge might be resolved when searches for bibliometric analysis are able to include into the full contents of published articles through the use of improved technologies, such as big data and artificial intelligence, instead of using limited and selected combination of keywords.

5. Conclusions

This paper evaluated the global research and publication trends in the remote sensing of PAs monitoring from 1991 to 2018. This analysis comprised eight main aspects: document types, publication output, subject categories, source journals, countries, organizations, and keywords. The results showed that since 2004, the number of publications increased rapidly and steadily. Environmental Sciences was the largest subject category. The highest number of papers was published in the two journals on Remote Sensing of Environment and Remote Sensing. The USA published the most in application of remote sensing technology in PA monitoring. Institutions affiliated to the USA have a massive number of publications and strong international collaboration in such type of explorations. Landsat, MODIS, and LiDAR are the most commonly used satellites and sensors. Most of the research was focused on classification, time-series analysis, and model methods. Keywords selections indicate that “Landsat”, “deforestation”, “LiDAR”, “conservation”, and “biodiversity” are among the most common subjects in the remote sensing of PAs. Studies on PA monitoring using remote sensing are mainly focused on change detection, biodiversity conservation, and the impact of climate change. In the future, we should continue to pay attention to the development trends and hot spots for the remote sensing monitoring of PAs. Researchers from all countries should strengthen the international exchanges of ideas and actively promote international research cooperation.

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