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Article

Forestry Applications of Space-Borne LiDAR Sensors: A Worldwide Bibliometric Analysis

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Abstract: The 21st century has seen the launch of new space-borne sensors based on LiDAR (light detection and ranging) technology developed in the second half of the 20th century. LiDAR was initially developed to integrate laser-focused imaging with the capability to determine distances through the measurement of signal return times, utilizing suitable sensors and data acquisition electronics. Nowadays, these sensors have transformed into robust instruments, offering novel opportunities for mapping terrain, canopy heights, and estimating above-ground biomass (AGB) across local to regional scales. This work aims to analyze the scientific impact of these sensors on large-scale forest mapping to retrieve 3D canopy information, monitor forest degradation, estimate AGB, and model key ecosystem variables such as primary productivity and biodiversity. In this way, a worldwide bibliometric analysis of this topic was carried out based on up to 412 publications indexed in the Scopus database during the period 2004–2022. The results showed that the number of published documents increased exponentially in the last five years, coinciding with the commissioning of two new LiDAR space missions: Ice, Cloud and Land Elevation Satellite (ICESat-2) and Global Ecosystem Dynamics Investigation (GEDI). These missions are providing data since 2018 and 2019, respectively. The journal that demonstrated the highest productivity in this field was "Remote Sensing," and among the leading contributors, the top five countries in terms of publications were the USA, China, the UK, France, and Germany. In the realm of prominent research institutions, France boasted six, the USA had four, China had three, while the UK and Canada each had one. The upward trajectory in the number of publications recorded from 2004 to 2022 categorizes the subject under investigation as a highly trending research topic, particularly within the context of enhancing the administration of forest resources and engaging in global climate treaty frameworks mandating the surveillance and reporting of carbon stocks in forests. The recent launch in August 2022 of the Terrestrial Ecosystem Carbon Monitoring Satellite (TECMS; China State Administration of Forestry and Grassland), along with the planned launch in the coming years of up to three new space sensors, such as the Multi-footprint Observation LiDAR and Imager (Japan Aerospace Exploration Agency), the BIOMASS P-band Synthetic Aperture Radar (SAR) (European Space Agency), and the LiDAR Surface Topography (LIST; NASA), will greatly contribute to expanding the ability to map and monitor forest systems at very large scales. In this context, the integration of space-borne data, including imagery, SAR, and LiDAR, is anticipated to steer the trajectory of this research in the upcoming years.

Keywords: space-borne LiDAR; ICESat; GEDI; forest; AGB; remote sensing; bibliometric analysis; Scopus

1. Introduction

Forest ecosystems offer a myriad of ecosystem services and social advantages, encompassing carbon sequestration, wildlife habitat, recreational opportunities, as well as the supply of both wood and non-wood products [1]. Therefore, assessing the value of ecosystem services rendered by forests is crucial for preventing or halting their degradation. This process involves the convergence of scientific, economic, and political domains to implement measures aimed at enhancing their sustainable management. Just to provide a quantitative figure referring to 1997, Costanza et al. [2] calculated the yearly value of ecosystem services provided by forests to be \$4.7 trillion, equivalent to around 15% of the World GNP (gross national product).

Forests encompass approximately 80% of the Earth's biomass, contributing to 75% of the gross primary productivity in the terrestrial biosphere [3]. They play a pivotal role in the global carbon cycle, constituting a significant component. In fact, forests account for up to 50% of the annual carbon exchange between the atmosphere and the Earth's land surface [4]. Functioning as natural carbon dioxide sinks, they effectively sequester atmospheric carbon, mitigating fossil fuel emissions at rates reaching about 30% [5].

However, a concerning deficiency exists in the standardization of forest monitoring data, posing a frequent impediment to decision-making processes related to both the economic facets of management activities and the environmental considerations tied to the impacts of climate change and anthropogenic pressures on forest protection by both public and private entities. Traditional terrestrial forest inventory methods that apply sampling procedures at plot level offer partial results that need to be extended by means of statistical inference to cover the entire forest mass [6,7]. This is an expensive and inefficient procedure that, moreover, is practically unfeasible in remote forest areas with difficult access [8]. In this sense, new forest evaluation and monitoring strategies are demanded, which is closely associated to the development of emerging spatial information technologies headed up to large-scale evaluation of key variables such as standing above-ground biomass (AGB). AGB serves as a metric for quantifying the capacity of forests to absorb carbon dioxide, being defined as the sum of living vegetation above the soil, encompassing the stem, stump, branches, bark, seeds, and foliage.

Remote sensing has demonstrated to be a cost-effective tool for AGB mapping on large scales, extending to national and even global extents [9]. Given the absence of a remote sensing sensor directly providing AGB information, studies rely on associated variables. Notably, "canopy height" emerges as a crucial variable obtainable from light detection and ranging (LiDAR) sensors, serving as a significant predictor for AGB [10–15]. Moreover, it aids in monitoring ecosystem responses to climate variations, forest degradation, land-use changes, and restoration efforts [16–19].

Historically, LiDAR data for forested areas primarily came from aircraft, limiting its spatial reach. Notably, aerial LiDAR surveys, due to their elevated costs, often prioritize data acquisition in high-value forest areas rather than offering comprehensive coverage at the national or regional levels [20,21]. However, a significant shift has occurred with the emergence of the new generation of space-borne LiDAR sensors, exemplified by missions like Ice, Cloud, and Land Elevation Satellite-2 (ICE-Sat-2) and Global Ecosystem Dynamics Investigation (GEDI), launched by NASA in 2018. Over the past five years, these sensors have gained prominence for their capability to directly furnish precise information on vertical vegetation structure on a global scale [22].

Satellite LiDAR measurement consists of transmitting laser pulses at a certain frequency from the space laser to Earth. In this way, the laser beam passes through the atmosphere and is scattered by the terrain/canopy surface, generating a weak backscattered echo. The satellite-based LiDAR telescope receives this energy return and the distance between the sensor and the target on Earth is calculated by converting photoelectric signals and measuring time. This computed distance is processed together with information from the satellite attitude, position, and laser pointing to directly produce accurate 3D spatial coordinates of the laser footprint point.

GEDI marked a pioneering achievement as the inaugural space-borne full waveform LiDAR (wavelength $\lambda=1064$ nm), uniquely designed to offer insights into the vertical structure of forest canopies [18,23], with a particular focus on Earth's temperate and tropical forests. Launched in

December 2018, it was installed on the International Space Station (ISS), boasting a footprint of 25 m (with planimetric uncertainty ranging from 8 to 10 m) at intervals of 60 m (along-track) and 600 m (across-track). Some of its derived products are L2A data (LiDAR metrics to determine terrain and vegetation height, vegetation cover, etc.) and L4A (AGB density based on calibrated models). GEDI full waveform data have additionally been employed in generating valuable derived data, including the Leaf Area Index (LAI) product. This product is made available globally through the NASA/USGS Land Processes Distributed Active Archive Center [24]. Due to the confined orbit of the ISS within the latitudes of 51.6° N and S, GEDI is unable to capture a substantial portion of the world's boreal forests, including regions like Canada.

Conversely, ICESat-2 faces no constraints in terms of orbit or data acquisition [19], ensuring comprehensive coverage of boreal forest regions. Equipped with the Advanced Topographic Laser Altimeter System (ATLAS), ICESat-2 features a micro-pulse, multi-beam photon-counting LiDAR sensor with a notable pulse repetition frequency of 10 kHz, a footprint of 10.9 ± 1.2 m, and a planimetric uncertainty of around 3.5 ± 2.1 m. The ATL03 data provided by ICESat-2 are employed in generating the land, water, and vegetation elevation product (ATL08 data). This product furnishes canopy height percentiles along 100 m segments by utilizing returned photons categorized as ground, noise, canopy, or top of canopy [20]. ATL08 supplies terrain elevation metrics like minimum, maximum, and average terrain heights, along with diverse canopy height metrics encompassing minimum, maximum, average canopy heights, and percentile canopy heights. The precision in retrieving canopy height is contingent on several influencing factors such as sensor characteristics (strong/weak beams), canopy structure (canopy cover and height), terrain (terrain slope), and external environmental conditions (solar angle and atmosphere scattering) [25]. This space-borne sensor is considered the successor to the first ICESat mission (2003-2009) that used a space-borne LiDAR sensor, the so-called Geoscience Laser Altimeter System (GLAS), to provide large-scale forest biomass and height maps.

Although GEDI and ICESat-2 are the more widely used space-borne LiDAR sensors currently, there are other space-borne laser altimeters worth discussing. This is the case with the Chinese satellites ZY3-02 and Gao Fen-7, launched in May 2016 and November 2019, respectively. ZY3-02 is equipped with high-resolution three-line CCD cameras that provide stereo mapping capabilities and a multispectral camera. It also counts on a very small and experimental laser altimeter that emits mono-beam discrete pulses with a ground footprint of about 50 m at a sample frequency of only 2 Hz. This low sample frequency implies that the spatial distance along the track between two adjacent footprints is considerable (approximately 3.5 km) [26]. As the ZY3-02 satellite laser altimeter was specifically designed to enhance the elevation accuracy of surveying and mapping satellite image products, it does not transmit back waveform data. Consequently, its applicability as a LiDAR system for forest applications is severely restricted. On the other hand, Gao Fen-7 comes equipped with a stereo mapping camera featuring a two-line-array and a laser altimeter system. This configuration allows for the simultaneous capture of stereo images and full waveform LiDAR data [27]. The dual-beam laser altimeter system on board emits laser pulses at 1064 nm to the ground, operating at an observing frequency of 3 Hz. This results in discrete laser footprints of approximately 20 m in diameter, with along-track and cross-track spacing measuring about 2.4 km and 12.25 km, respectively. The primary limitation of this space-borne LiDAR sensor lies in its low footprint density on the ground. Full waveform data are recorded at 2 GHz with a sampling interval of 7.5 cm [28].

Over the past half-decade, space-borne LiDAR has emerged as a pivotal technology, furnishing precise information on the interconnections between biodiversity and ecosystem structure [21]. In this way, space-borne LiDAR data can accurately describe the vertical structure of the forest. However, its discrete point distribution of data acquisition hardly supports continuous forest management planning. Overall, it is mandatory to combine space-borne LiDAR data with other imaging remote sensing technologies (Sentinel-1, Sentinel-2, etc.) to obtain wall-to-wall forest height for resource management, policy development and decision making at regional or even nationwide studies [24,29].

Considering the context outlined in the preceding paragraph, the recent launch in August 2022 of the Terrestrial Ecosystem Carbon Monitoring Satellite (TECMS; China State Administration of Forestry and Grassland), coupled with the introduction of a new generation of space-borne active sensors like Multi-footprint Observation LiDAR and Imager (MOLI; Japan Aerospace Exploration Agency), BIOMASS P-band Synthetic Aperture Radar (SAR) (European Space Agency), and LiDAR Surface Topography (LIST; NASA), is poised to significantly enhance the array of space-based sensors available for mapping and monitoring extensive forest systems.

2. Materials and Methods

2.1. Bibliometric methods

A conventional bibliometric analysis of scientific documents was conducted using co-occurrence analysis applied to database metadata, as detailed in [30]. This analysis followed indicators related to productivity, quality, and structure, as outlined in [31].

Concerning productivity indicators, the bibliometric analysis concentrated on the count of indexed articles and conference papers associated with the core theme of "Space-borne LiDAR in forestry applications." Additionally, it explored the contributors, journals, institutions, and countries associated with these documents.

The evaluation of scientific quality indicators in this study involved several established parameters, including the number of citations, the author/journal h-index [32], and the Scimago Journal Rank (SJR) impact factor of journals [33]. The latter two indices were devised to enhance straightforward metrics such as the total number of citations or publications. It is important to note that the journal/author h-index is defined as the maximum value of h, indicating that the given journal/author has published h papers, each cited at least h times. This metric takes into account both quantity (number of articles) and scientific impact or quality (number of citations). Concerning the assessment of the journal's impact (journal ranking), the SJR index is calculated as the ratio between the average number of weighted citations received in a year and the number of documents published in the journal over the previous three years. Therefore, SJR considers not only the number of citations received by a journal but also the importance and prestige associated with the source of those citations [33].

Ultimately, certain structural indicators were formulated to uncover linkages among scientific actors and pinpoint research trends related to the topic. This involved utilizing mapping tools like VOSviewer [34,35].

2.2. Data processing

For this study, the Scopus database was selected as it stands as the most extensive repository of peer-reviewed literature [36]. In fact, Scopus includes a greater number of indexed journals compared to Web of Science (WoS) [37]. Notably, approximately 84% of the titles indexed in WoS are present in Scopus, while only 54% of the publications indexed in Scopus are mirrored in WoS [38].

The keywords and search string inputted into Scopus to identify relevant indexed publications for this bibliometric analysis comprised the following:

TITLE-ABS-KEY ((icesat OR "spaceborne lidar" OR gedi) AND (forestry OR forestal OR forests OR forest)) AND (EXCLUDE (PUBYEAR , 1963) OR EXCLUDE (PUBYEAR , 1998) OR EXCLUDE (PUBYEAR , 2003) OR EXCLUDE (PUBYEAR , 2023)) AND (LIMIT-TO (EXACTKEYWORD , "Forestry") OR LIMIT-TO (EXACTKEYWORD , "Biomass") OR LIMIT-TO (EXACTKEYWORD , "Vegetation") OR LIMIT-TO (EXACTKEYWORD , "Aboveground Biomass") OR LIMIT-TO (EXACTKEYWORD , "Above Ground Biomass") OR LIMIT-TO (EXACTKEYWORD , "Canopy Heights") OR LIMIT-TO (EXACTKEYWORD , "Forest Canopy") OR LIMIT-TO (EXACTKEYWORD , "Ecosystem Dynamics") OR LIMIT-TO (EXACTKEYWORD , "Canopy Height") OR LIMIT-TO (EXACTKEYWORD , "Forest Height") OR LIMIT-TO (EXACTKEYWORD , "Forest") OR LIMIT-TO (EXACTKEYWORD , "Forest Ecosystem") OR LIMIT-TO (EXACTKEYWORD , "Forest Structure") OR LIMIT-TO (EXACTKEYWORD , "Forest Biomass") OR LIMIT-TO (EXACTKEYWORD ,

"Forests") OR LIMIT-TO (EXACTKEYWORD , "Tropical Forest") OR LIMIT-TO (EXACTKEYWORD , "Forest Canopies") OR LIMIT-TO (EXACTKEYWORD , "Vegetation Mapping") OR LIMIT-TO (EXACTKEYWORD , "Vegetation Structure") OR LIMIT-TO (EXACTKEYWORD , "Tree Height") OR LIMIT-TO (EXACTKEYWORD , "Boreal Forest") OR LIMIT-TO (EXACTKEYWORD , "Forest Inventory") OR LIMIT-TO (EXACTKEYWORD , "Forest Cover") OR LIMIT-TO (EXACTKEYWORD , "Canopy Height Models") OR LIMIT-TO (EXACTKEYWORD , "Canopy Architecture") OR LIMIT-TO (EXACTKEYWORD , "Forest Aboveground Biomass") OR LIMIT-TO (EXACTKEYWORD , "Forest Canopy Height") OR LIMIT-TO (EXACTKEYWORD , "Vegetation Height") OR LIMIT-TO (EXACTKEYWORD , "Vegetation Cover") OR LIMIT-TO (EXACTKEYWORD , "Forest Management") OR LIMIT-TO (EXACTKEYWORD , "Canopy Cover") OR LIMIT-TO (EXACTKEYWORD , "Biomass Estimation") OR LIMIT-TO (EXACTKEYWORD , "AGB")) AND (EXCLUDE (LANGUAGE , "Chinese") OR EXCLUDE (LANGUAGE , "Russian")).

This search was conducted in 2023, comprising a target study period from 2004 to 2022. An attempt was made to encompass all indexed Scopus items, including document types such as articles, reviews, letters, and conference papers. It is noteworthy that only documents dated up to 2022 were considered to facilitate comparisons across complete 12-month periods [39]. The variables under investigation included the number of publications per year, document type, author, institution, country, subject area, journal, and keywords.

Several preprocessing tasks were executed to rectify common errors, including duplications, misspellings, and variant names [40]. Following a manual review involving keyword analysis, author scrutiny, and abstract reading, the initial number of documents was reduced to 412, discarding the majority of them.

Upon downloading all data in RIS and CSV formats, meticulous manual processing ensued to eliminate duplicates and unrelated elements, resulting in a refined database. This finalized database served as the foundation for generating various tables and figures to streamline the analysis of the collected information. Both Excel (version 2016, Microsoft) and SciVal (Elsevier) were employed for these tasks. Additionally, VOSviewer played a role in constructing the relevant network maps [41] (see Figure 1). An extra examination of pertinent keywords was conducted using the VOSviewer tool to create a network of co-occurring keywords, shedding light on current research trends within the topic of interest.

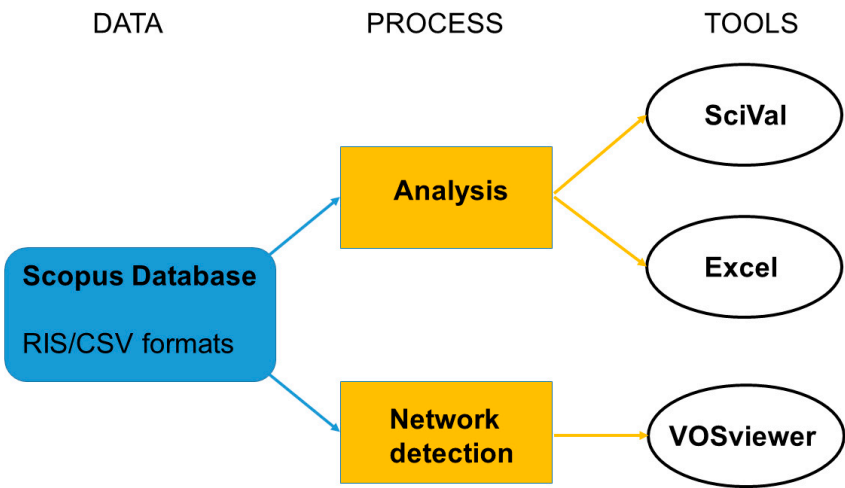


Figure 1. Data screening and analysis. Simplified flowchart.

3. Results

3.1. Scientific Production and Characteristics

The searched period from 2004 to 2022 yielded 412 documents (access in RIS and BIB format at this [link](#)), including 303 articles (73.5%), 94 conference papers (22.8%), 13 reviews (3.2%), one book chapter (0.2%), and one note (0.2%). Examining the publication trends reveals a growing interest in the research on "Forest applications of Space-borne LiDAR sensor" in recent years (see Table 1). Notably, the majority of documents (51.45%) surfaced within the last four years (2019-2022), with the peak number of publications occurring in 2022 (19.90%). This substantiates that "Forestry applications of space-borne LiDAR sensors" is a burgeoning subject in constant evolution, and it is likely to witness a surge in publications in the upcoming years, particularly with the deployment of the Terrestrial Ecosystem Carbon Monitoring Satellite (China), the Multi-footprint Observation LiDAR and Imager (Japan), and the LiDAR Surface Topography (United States).

Figure 2 shows an exponentially increasing relationship ($R^2 = 0.8141$) between the number of documents published over time during the period 2004-2022. This growing interest of the scientific community on this topic can be justified by the urgent need to collect accurate, timely and large-scale information related to AGB and carbon stocks fixed by forests. The utilization of remote sensing monitoring is deemed essential within the framework of the United Nations Framework Convention on Climate Change, particularly in the context of the strategy for Reducing Emissions from Deforestation and Forest Degradation (REDD) [42].

Upon dissecting the bibliometric data showcased in Table 1, a notable escalation is evident. The number of authors (AU) surged from a mere four in 2004 to 588 in 2022, paralleled by the escalation in the number of publications in journals (J) from one in 2004 to 82 in 2022. This heightened scientific impact is further underscored by the extensive references, reaching up to 4383 (number of references; NR), cited in the 82 articles published in 2022, along with the cumulative total citations (TC) amounting to 12419 across the 412 sample documents collected from 2004 to 2022.

In summary, the forestry applications of space-borne sensors have become an appreciated and valued tool for providing wall-to-wall AGB estimates and information on vertical vegetation structure. This evidence is notably encouraging developed countries to maintain current space-borne LiDAR programs and initiate new ones, not necessarily based on LiDAR technology but also on space-borne SAR sensors (e.g. BIOMASS P-band SAR powered by the European Space Agency).

Table 1. Key attributes of documents pertaining to the topic between 2004 and 2022.

Years	A	NR	NR/A	TC	TC/CA	AU	AU/A	J	C
2004	1	0	0.0	13	13.0	4	4.0	1	2
2005	1	14	14.0	527	527.0	8	8.0	1	3
2006	4	35	8.8	31	7.8	16	4.0	2	4
2007	2	30	15.0	246	123.0	11	5.5	2	4
2008	9	246	27.3	986	109.6	39	4.3	7	7
2009	8	262	32.8	316	39.5	35	4.4	7	11
2010	17	411	24.2	932	54.8	56	3.3	14	7
2011	18	708	39.3	1543	85.7	77	4.3	16	7
2012	13	436	33.5	862	66.3	94	7.2	10	11
2013	17	564	33.2	527	31.0	101	5.9	15	14
2014	23	898	39.0	750	32.6	131	5.7	23	15
2015	29	1425	49.1	726	25.0	160	5.5	24	17
2016	19	961	50.6	587	30.9	101	5.3	17	12
2017	24	1263	52.6	1002	41.8	124	5.2	24	15
2018	15	791	52.7	308	20.5	105	7.0	14	13
2019	41	1948	47.5	1238	30.2	244	6.0	41	19
2020	38	1988	52.3	758	19.9	237	6.2	36	19

2021	51	2892	56.7	810	15.9	290	5.7	48	20
2022	82	4383	53.5	257	3.1	588	7.2	82	38
Total	412	19255	46.7*	12419	30.1*	2421**	5.9*	384	54**

A: Annual number of total documents; NR: Number of references in total publications; NR/A: Annual number of references per publication; TC: Annual number of citations in cumulative publications; TC/CA: Annual total citations per cumulative publication, AU: Annual number of authors; J: Annual number of publications in journals; C: Annual number of countries. *: Average value. **: Total participants.

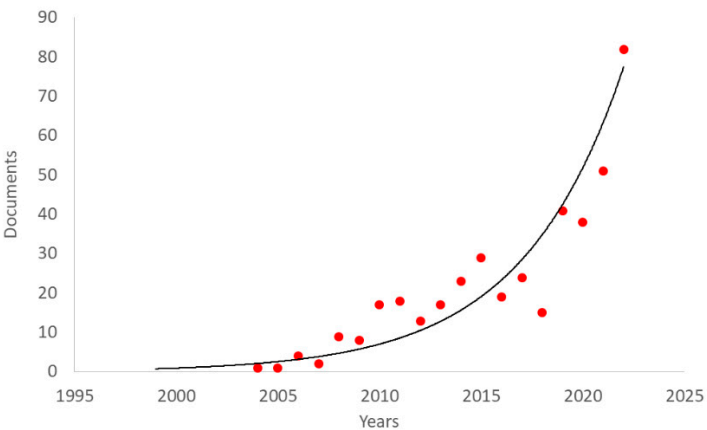


Figure 1. Evolution in the count of published documents (exponential fit with $R^2 = 0.8141$).

3.2. Subject Categories and Journals/Conferences

The 412 documents published from 2004 to 2022 were categorized into 10 different groups according to the Scopus database. Figure 3 illustrates the temporal evolution of the primary thematic categories assigned by Scopus to these 412 documents. It is worth noting that each document may fall into two or more categories simultaneously. In this way, a substantial portion of the sample was classified across five domains, encompassing up to 85.4% of the published documents. They were Earth and Planetary Sciences (44.6%), Agricultural and Biological Sciences (14.6%), Computer Science (12.0%), Environmental Science (8.4%), and Engineering (5.9%). A consistent pattern emerges toward the end of the period, where the Earth and Planetary Sciences category stands out as the predominant, followed by Agricultural and Biological Sciences and Environmental Science.

The 10 journals and conferences indexed in Scopus with the highest number of works published between 2004 and 2022 are listed in Table 2 grouped into five periods. The analysis discloses that the most prolific journal in the subject under scrutiny was "Remote Sensing," securing the top position among leading journals with 90 documents. The inaugural article in this journal (first A in Table 2) surfaced in 2011, although it only claimed the top spot in terms of article count during the fourth sub-period (2015-18). Following closely in the ranking for publishing articles on "forest applications of space-borne LiDAR sensors" is "Remote Sensing of Environment," a highly impactful journal that held the premier position in the third sub-period (2011-14).

Concerning the impact indicators of journals, "Remote Sensing of Environment" emerges as the journal with the highest total number of citations, boasting 4444 citations. It is significantly ahead of other journals, with "Remote Sensing" accumulating 1454 citations and "International Journal of Remote Sensing" securing 633 citations (Table 2). It is relevant to highlight that "Remote Sensing of Environment" and "International Journal of Remote Sensing" are the journals that published articles with the greatest impact on the topic studied, showing the highest number of citations per article published with 61.7 and 48.7 citations, respectively. The journal "Remote Sensing" presented an average value of 16.2 citations/article, although it is the most important journal if we consider the total number of published documents.

With respect to quality indices (Table 2), "Remote Sensing of Environment" leads with the highest SJR index of 4.057, trailed by "Environmental Research Letters" with a SJR index of 2.119. The majority of the analyzed documents were positioned within the first quartile based on their SJR index in the 2022 edition, underscoring the elevated quality of the international journals addressing this emerging topic. It is essential to note that an SJR index exceeding 1.5 typically correlates with a highly cited journal.

Looking at the h-index (2022 SJR edition), "Remote Sensing of Environment" presents the highest value (327), followed by "International Journal of Remote Sensing" (195) and "Proceedings of SPIE - The International Society for Optical Engineering" (187). Note that prestigious journals such as "Remote Sensing" (168) and "Environmental Research Letters" (164) are one-step below. For "Remote Sensing," being a relatively recent entrant, it has not accumulated sufficient citations to elevate its h-index at this point.

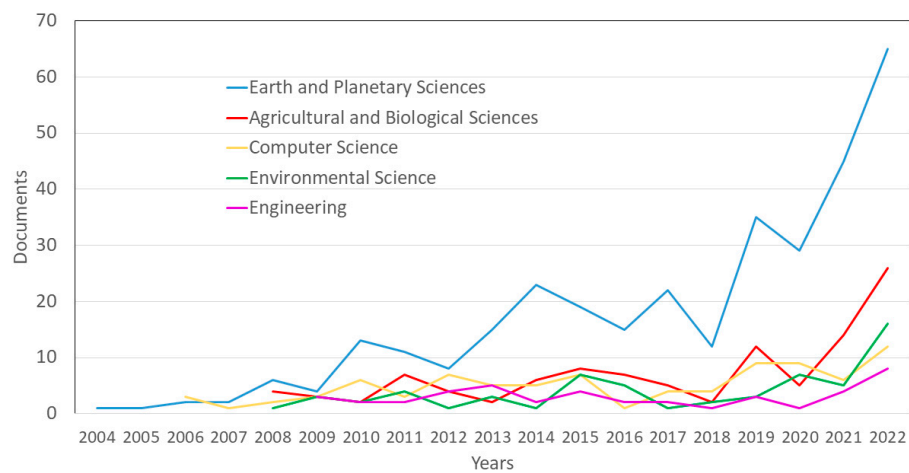


Figure 2. Distribution of publications over time according to Scopus sub-areas category.

Table 2. Characteristics of the top 10 most productive Scopus indexed journals and conferences from 2004 to 2022.

Journal/Conference	A	SJR	C	TC	TC/A	h	1st A	A (R)				
								2004-2006	2007-2010	2011-2014	2015-2018	2019-2022
Remote Sensing	90	1.136 (Q1)	Switzerland	1454	16.2	168	2011	0	0	6 (3)	16 (1)	68 (1)
Remote Sensing of Environment	72	4.057 (Q1)	United States	4444	61.7	327	2008	0	5 (2)	15 (1)	11 (2)	41 (2)
International Geoscience and Remote Sensing Symposium (IGARSS)	42	0.255	United States	109	2.6	79	2004	3 (1)	3 (3)	11 (2)	4 (7))	21 (3)
IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing	16	1.264 (Q1)	United States	339	21.2	114	2013	0	0	5 (4)	7 (3)	4 (7)
International Journal of Remote Sensing	13	0.732 (Q1)	United Kingdom	633	48.7	195	2008	0	6 (1)	2 (8)	5 (4)	0
International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives	12	0.274	Germany	76	6.3	82	2006	1 (2)	2 (5)	1 (10)	4 (6)	4 (8)
International Journal of Applied Earth Observation and Geoinformation	12	1.628 (Q1)	Netherlands	297	24.8	120	2010	0	1 (6)	2 (7)	4 (5)	5 (6)
IEEE Geoscience and Remote Sensing Letters	11	1.284 (Q1)	United States	129	11.7	138	2013	0	0	3 (6)	0	8 (4)
Proceedings of SPIE - The International Society for Optical Engineering	10	0.166	United States	12	1.2	187	2009	0	3 (4)	5 (5)	2 (8)	0
Environmental Research Letters	8	2.119 (Q1)	United Kingdom	111	13.9	164	2011	0	0	1 (9)	0	7 (5)

A: number of total publications; SJR: Scopus Journal Ranking (2022); C: country; TC: number of citations in total publications; TC/A: total citations per publication; h: journal h-index (year 2022); 1st A: first publication research by journal; R: ranking position (1st Documents, 2nd SJR).

3.3. Countries, Institutions, and Authors

The topic “Forest applications of space-borne LiDAR sensors” was investigated during 2004-2022 by researchers from up to 53 countries, demonstrating its great interest worldwide (Table 3). It is important to highlight that a single document could be attributed to multiple countries if the authors hailed from different nationalities, indicating international collaboration. The United States reached the top position with 183 publications, followed by China with 117, and, at a greater distance, the United Kingdom with 44 publications. Note that 47.5% of the publications from the United States were released in the most recent sub-period under examination. Table 3 additionally illustrates the number of documents published per million inhabitants of each country (APC). When considering this productivity ratio relative to the country's population, the Netherlands claimed the top spot at 0.86, closely followed by Canada at 0.84.

Concerning the scholarly impact of the scrutinized documents, the United States accumulated the highest number of citations, totaling 8377, followed by China (1788), Canada (1699), and the United Kingdom (1654) in a distinct lower tier. However, when examining the number of citations per publication, Canada secured the top position with 53.09 citations per publication, closely followed by the United States (45.78) and the United Kingdom (37.59).

Table 3. The 10 most productive countries according to research on the topic "Forest applications of space-borne LiDAR" (2004-2022).

COUNTRY/TERRITORY	A	APC	TC	TC/A	Documents (A)				
					2004-2006	2007-2010	2011-2014	2015-2018	2019-2022
United States	183	0.54	8377	45.78	4	22	33	37	87
China	117	0.08	1788	15.28	0	11	16	28	62
United Kingdom	44	0.66	1654	37.59	0	4	9	12	19
France	39	0.58	595	15.26	0	0	13	10	16
Germany	33	0.40	370	11.21	0	1	6	4	22
Canada	32	0.84	1699	53.09	0	5	6	7	14
India	21	0.01	180	8.57	0	0	2	4	15
Australia	16	0.64	307	19.19	1	1	1	4	9
Netherlands	15	0.86	381	25.40	1	3	2	1	8
Spain	15	0.32	185	12.33	0	0	1	2	12

A: number of total publications; APC: number of documents per 1 million inhabitants; TC: number of citations in total publications; TC/A: total citations per publication.

Figure 4 shows a network showcasing international collaboration among publishing countries. The size of each circle corresponds to the number of publications from each country, and the thickness of the lines connecting two collaborating countries is directly proportional to the number of collaborations between them. Note that only one group in red could be extracted, which means that the international network that works on this topic collaborates frequently, with no clearly independent or isolated research groups existing. This cluster focuses on the US as the country that presents the greatest scientific production on the topic analyzed, also highlighting the very intense collaboration between the US and China, and the less important collaboration between the US and the United Kingdom.

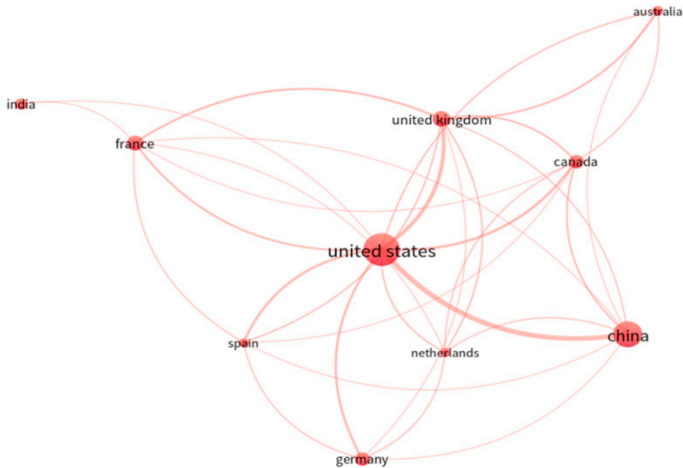


Figure 3. Collaboration network based on co-authorship among countries.

Table 4 provides quantitative information on international collaborations among the most prolific countries according to the percentage of publications each country generated in collaboration with others (IC), the count of countries involved in such collaborations (NC), and the principal collaborating countries. Based on this data, it can be affirmed that all countries released documents created through collaborations with other nations. The United States stands out as the country most actively engaged in international collaboration networks, with up to 44.42% of its documents developed in collaboration with other countries. In this way, the United States and France were the countries with the highest number of collaborations with other countries (41 and 39, respectively). It is important to emphasize that there is no clear relationship between international collaboration and scientific impact (measured as total citations by publications segregated by international collaboration (IC) and non-international collaboration (NIC)) (Table 4), varying greatly between countries.

Table 4. International research collaboration on the topic between countries from 2004 to 2022.

Country	IC%	NC	Main Collaborators (A)	TC/A	
				IC	NIC
United States	44.42%	41	China (42), United Kingdom (22), Canada (11), Spain (10), Germany (9), Gabon (8), Norway (8)	48.01	16.35
China	28.40%	31	United States (42), Canada (5), Netherlands (3), United Kingdom (3)	16.30	35.95
United Kingdom	10.68%	34	United States (22), France (8), Australia (7), Gabon (7)	39.82	29.29
France	9.47%	39	United Kingdom (8), Brazil (7), United States (7), Gabon (6)	16.49	31.87
Germany	8.01%	33	United States (9), Netherlands (3), Norway (3), Spain (3)	12.67	31.96
Canada	7.77%	32	United States (11), United Kingdom (6), China (5), Norway (4)	55.47	28.30
India	5.10%	21	Estonia (1), France (1), Italy (1), United States (1)	9.29	31.55
Australia	3.88%	16	United Kingdom (7), United States (4), Canada (3), China (2)	21.00	30.79
Netherlands	3.64%	15	United Kingdom (4), United States (4), Austria (3), Canada (3)	27.53	30.52

Spain	3.64%	15	United States (10), Portugal (4), United Kingdom (4), France (3)	15.73	30.97
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IC: international collaborations; NC: total number of international collaborators; TC/A: total citations per publication; NIC: non-international collaborations.

Table 5 outlines the primary production and impact indicators of institutions with the most significant number of publications. It is noteworthy that since some publications involve researchers from different countries and institutions, the total number of publications per country/institution in Table 5 surpasses the count of publications in the overall sample (412).

The University of Maryland, College Park, achieved the top position with a total of 77 publications from 2004 to 2022, closely followed by NASA Goddard Space Flight Center (54 documents) and the Chinese Academy of Sciences (51 documents). CIRAD contributed 24 publications but at a greater distance. In terms of scientific impact, measured by the total number of citations, the University of Maryland counted on 3701 citations, closely trailed by NASA Goddard Space Flight Center with 3478. However, when examining the average number of citations per publication, Natural Resources Canada emerged as the leader, averaging 80.29 citations per document across 17 articles published in the analyzed period. The California Institute of Technology secured the second position with 79.10 citations per publication and 20 publications. Lastly, the Jet Propulsion Laboratory and the University of Edinburgh exhibited the highest percentage of collaborative works, with 73.91% and 73.68%, respectively.

Table 5. Characteristics of the main institutions on the topic analyzed from 2004 to 2022.

Nº	Institution	C	A	TC	TC/A	IC (%)
1	University of Maryland, College Park	USA	77	3701	48.06	68.83%
2	NASA Goddard Space Flight Center	USA	54	3478	64.41	59.26%
3	Chinese Academy of Sciences	China	51	1241	24.33	54.90%
4	CIRAD	France	24	393	16.38	62.50%
5	Jet Propulsion Laboratory	USA	23	1808	78.61	73.91%
6	INRAE	France	23	328	14.26	52.17%
7	State Key Laboratory of Remote Sensing Science	China	23	561	24.39	65.22%
8	AgroParisTech	France	22	299	13.59	50.00%
9	Territoires, Environnement, Télédétection et Information Spatiale	France	22	299	13.59	45.45%
10	University of Chinese Academy of Sciences	China	21	450	21.43	57.14%
11	California Institute of Technology	USA	20	1582	79.10	70.00%
12	The University of Edinburgh	United Kingdom	19	704	37.05	73.68%
13	CNRS Centre National de la Recherche Scientifique	France	18	290	16.11	55.56%
14	Natural Resources Canada	Canada	17	1365	80.29	52.94%
15	IRD Centre de Montpellier	France	17	248	14.59	52.94%

C: country; A: number of total publications per institution; TC: number of citations in total publications; TC/A: total citations per publication; IC (%): percentage of international collaborations (number of international collaborations/A).

Figure 5 illustrates a network map depicting collaborative co-authorship dynamics from 2004 to 2022. Various colors designate groups corresponding to authors who frequently collaborate with one another. The map selectively displays the most interconnected co-authorships. The results shown in Figure 5 have a minimum of six connections. The size of the sphere associated with each author is proportional to the number of published documents. Although several groups were drawn, only

three groups have been noted. The group on the right (yellow circle) is made up mainly of French authors (Fayad, I. and Baghdadi, N.), while the group surrounded by a red circle is made up of several subgroups, most of them including authors from the United States (Sung, G., Dubayah, R. and Armston, J.), the United Kingdom (Hancock, S.) and Canada (Coops, N.C., Wulder, M.A.). The last main group is surrounded in green and is mainly composed of authors from China (Wang, C., Pang, Y., and Xing, Y.). Therefore, these three clusters can be considered the three most relevant research networks on the topic analyzed currently in the world. In any case, a highly complex collaboration network is observed within it, with the exception of the French cluster.

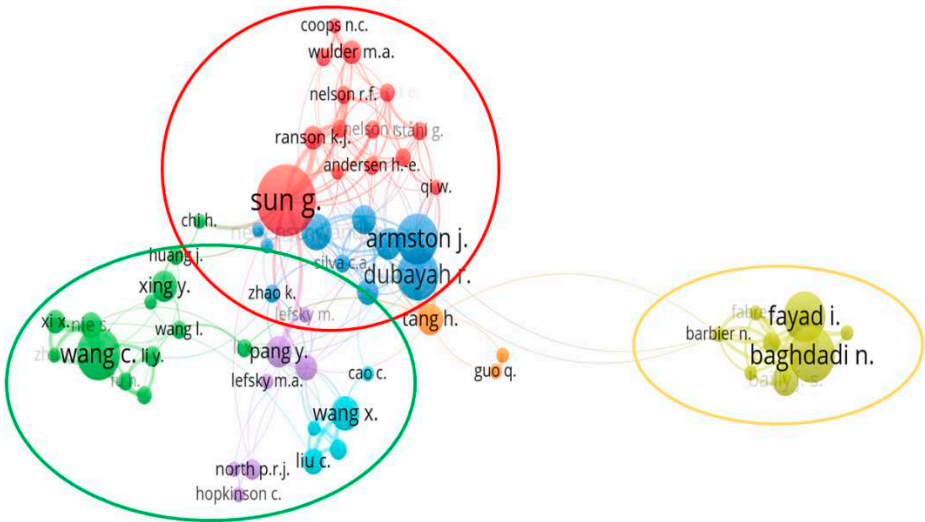


Figure 4. Collaboration network based on co-authorship between authors.

Table 6 outlines the 14 most prolific authors within the scope of the topic examined in this study. It encompasses parameters related to both productivity (A) and the scholarly impact of the publications (total citations; TC). Additionally, the table includes pertinent reference data associated with each author, such as author affiliation, country (C), year of initial publication (First P), and the most recent publication (Last P) within this topic.

The initial three authors in the ranking were affiliated with the University of Maryland (College Park) in the United States, each contributing to more than 20 publications. All authors listed in Table 6 hail from the four most prolific countries (Table 3) and are affiliated with nine different institutions. The most productive authors turned out to be Sun, G. from the United States. Note that all authors featured in Table 6 remain active in this field, as evidenced by their latest publications spanning from 2019 to 2022.

Table 6. The most productive authors on the topic analyzed during the period 2004-2022.

Authors	A	TC	h-index	C	Affiliation	First P	Last P
Sun, G.	27	1151	39	United States	University of Maryland, College Park	2004	2019
Dubayah, R.	22	957	56	United States	University of Maryland, College Park	2006	2022
Armston, J.	21	857	24	United States	University of Maryland, College Park	2015	2022
Baghdadi, N.	21	274	53	France	Irstea, Antony	2013	2022
Fayad, I.	19	266	13	France	Université de Montpellier	2014	2022
Hancock, S.	16	492	25	United Kingdom	The University of Edinburgh	2012	2022
Tang, H.	15	698	18	Singapore	National University of Singapore	2014	2022

Duncanson, L.	14	473	23	United States	University of Maryland, College Park	2017	2022
Neuenschwander, A.	14	784	23	United States	The University of Texas at Austin	2010	2022
Wang, C.	13	216	30	China	Aerospace Information Research Institute, Beijing	2011	2022
Bailly, J.S.	12	234	26	France	AgroParisTech	2014	2022
Pang, Y.	12	424	24	China	Chinese Academy of Forestry	2007	2019
Xing, Y.	12	134	11	China	Northeast Forestry University	2008	2022
Nie, S.	10	177	19	China	Aerospace Information Research Institute	2015	2022

A: Documents; TC: Total Citations; C: Country; First P: first year publication; Last P: last year publication.

3.4. Keyword Analysis

Table 7 presents the top 20 keywords extensively utilized in the analyzed topic from 2004 to 2022. This period is segmented into five sub-periods to facilitate a comprehensive understanding of keyword usage and its evolution over time. The variables detailed in Table 7 include the keywords' position in the ranking (R) within each sub-period relative to the total number of keywords in the sample for that period, the frequency of their appearance in publications (A), and the percentage of repetition (%). "Forestry" and "Optical Radar" emerge as the most recurrent keywords throughout the entire study period, consistently claiming top positions in the sub-period rankings. It is important to note that the term "Optical Radar" is another way of referring to the LiDAR sensor.

In the initial sub-period of 2004-2006, the following two frequently mentioned keywords on the list were "Remote Sensing" and "Biomass", without including LiDAR in either of its two versions ("Lidar", more frequent, or "LiDAR", less frequent). At this early time was much more frequent to use the term "Optical Radar" to denote LiDAR. In the second sub-period (2007-2010), researchers' keyword preferences underwent a slight shift. While "Optical Radar" maintained its position in the second slot in the ranking, there were some alterations in the overall pattern, with keywords like "Aneroid Altimeters" and "Radio Altimeters" emerging and climbing to third and fourth position, respectively. It is worth clarifying that the aneroid altimeter, also known as an aneroid barometer, is distinct from a LiDAR sensor because it functions as a tool to measure altitude above sea level. Conversely, a radio altimeter determines absolute altitude, indicating the distance above land or water. This determination is based on the principle of reflecting electromagnetic wave pulses off the surface of the Earth or sea. The terms "Lidar" and "LiDAR" also appeared to reach fifth position in the case of the former. The sub-periods spanning 2011-2014 and 2015-2018 marked a transition towards the current configuration of the keyword research framework, also facilitated by the drastic increase in the number of publications on the topic with the design, simulation analysis and final launching of the space-borne LiDAR sensors ICESat-2 and GEDI. The keyword "Lidar" managed to occupy third/fourth place in the ranking, in clear competition with the keyword "Remote Sensing". It is necessary to highlight that "Optical Radar" continued to maintain its second position as a frequent physical term to refer to LiDAR technology. The concluding period from 2019 to 2022 continued the trend established in the two preceding sub-periods. Consequently, the final classification aligned closely with the pattern observed in the recent sub-periods, primarily driven by the surge in publications and the consequent expansion in the repertoire of keywords employed in recent years.

Table 7. The top 20 most frequently used keywords on the topic analyzed from 2004 to 2022.

Keywords	2004-2022			2004-2006			2007-2010			2011-2014			2015-2018			2019-2022		
	A	%	R	A	%	R	A	%	R	A	%	R	A	%	R	A	%	R
Forestry	282	68.4%	1	6	100%	1	23	64%	1	40	56%	1	59	68%	1	154	73%	
Optical Radar	252	61.2%	2	4	67%	2	23	64%	2	40	56%	2	43	49%	2	142	67%	

Remote Sensing	173	42.0%	4	3	50%	6	16	44%	3	36	51%	4	31	36%	3	87	41%
Lidar	155	37.6%		0	0%	5	17	47%	4	32	45%	3	31	36%	4	75	35%
Biomass	119	28.9%	5	2	33%	8	14	39%	6	22	31%	6	29	33%	6	52	25%
Aneroid Altimeters	106	25.7%	11	1	17%	3	21	58%	9	18	25%	5	30	34%	16	36	17%
Vegetation	102	24.8%	7	2	33%	7	15	42%	10	18	25%	9	25	29%	12	42	20%
Radio Altimeters	99	24.0%	64	1	17%	4	21	58%	12	16	23%	8	28	32%	20	33	16%
ICESat	91	22.1%	48	1	17%	24	6	17%	7	19	27%	7	28	32%	15	37	17%
Aboveground Biomass	79	19.2%	9	1	17%	16	7	19%	16	13	18%	11	17	20%	13	41	19%
Ecosystems	72	17.5%	6	2	33%	61	3	8%	46	6	8%	14	17	20%	7	44	21%
GEDI	67	16.3%		0	0%		0	0%		0	0%	99	3	3%	5	64	30%
NASA	66	16.0%	59	1	17%	74	3	8%	32	9	13%	38	9	10%	8	44	21%
Satellite Data	65	15.8%	68	1	17%	34	5	14%	15	14	20%	21	13	15%	21	32	15%
Mean Square Error	60	14.6%		0	0%	122	2	6%		2	3%	20	13	15%	10	43	20%
Land Elevation Satellites	58	14.1%		0	0%	32	5	14%	43	7	10%	27	11	13%	19	35	17%
Satellites	56	13.6%	69	1	17%	9	14	39%	8	19	27%	34	10	11%	62	12	6%
Synthetic Aperture Radar	56	13.6%		0	0%		0	0%	70	4	6%	35	10	11%	11	42	20%
GLAS	55	13.3%		0	0%	22	6	17%	24	11	15%	10	22	25%	50	16	8%
LiDAR	55	13.3%		0	0%	17	7	19%	17	13	18%	17	14	16%	36	21	10%

A: Documents; R: Ranking of the total Keywords in this period; %: In how many documents appears this keyword about the total documents in this period.

Figure 6 depicts a network map interconnecting various keywords related to the scrutinized publications. Each circle's size corresponds to the number of publications featuring the respective keyword, while the color designates the cluster to which the keyword belongs, determined by the frequency of co-occurrences. In this sense, the green cluster centers around the term "Forest," standing out as the cluster with the highest number of connections and exhibiting the closest association with forestry applications. The red cluster presents "Lidar" as its main keyword, which mainly involves data processing methods and complementary technologies. The blue cluster includes keywords such as "Radio altimeters", "earth elevation satellites", "digital elevation model" and "landforms", being a cluster more focused on geosciences and terrain modeling. The yellow cluster grouped keywords mainly related to machine learning methods and other data sources (Landsat, Sentinel-1, ALOS PALSAR).

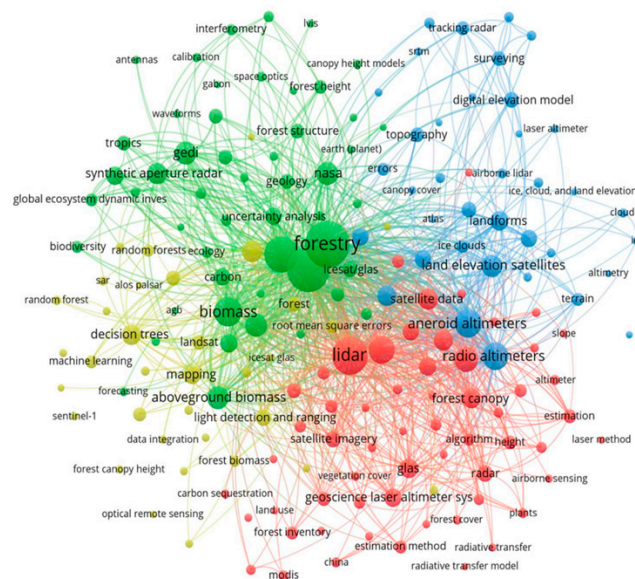


Figure 5. Keywords network on the topic analyzed for the period 2004-2022.

4. Discussion

First of all, it is necessary to clarify the objective of this study, which focuses on carrying out a bibliometric analysis that provides a quantitative framework to understand the evolution and current situation of the topic “Forest applications of space-borne LiDAR sensors” from 2004 to 2022. With this objective in mind, we analyzed several objective indicators grouped into five categories: (i) evolution of scientific production, (ii) main actors involved, (iii) information dissemination (indexed journals/conferences and keywords), (iv) scientific impact, and (v) scientific collaboration networks. It is noteworthy that bibliometric methods have become an integral component of research evaluation methodology, particularly in the scientific and applied domains [43]. Therefore, it would be a mistake to confuse the approach applied in this work with the typical approach used when writing a review article. In this paper, we conducted a bibliometric analysis utilizing relevant statistical data, providing a suitable approach to assess the scientific production within the studied topic. The outcomes are presented for the benefit of researchers, policymakers, and other stakeholders [43].

The topic under study has proven to be an emerging research discipline in the field of remote sensing only in the last five years due to two concomitant facts. First, the most important space LiDAR sensors, i.e. ICESat-2 and GEDI, were launched in 2018 and became fully operational in 2019. Before that, only ICESat-1 (launched in January 2003 and operated until February 2010) and some experimental laser altimeters were available (e.g. ZY3-02 and Gao Fen-7). Without a doubt, the launch into orbit in 2018 of the two LiDAR sensors mentioned has marked a great change in the evolution of AGB estimation using LiDAR technology. Second, the predominant research themes in space-borne LiDAR studies have consistently revolved around forest inventory and forest productivity [22] because there is a clear need to know what is the carbon stock fixed by forests. In other words, it is evident that the pivotal role of effectively monitoring forests on a large scale is crucial for adapting to climate change [1,44]. Note that terrestrial carbon budget due to land use change and carbon absorption by forests are more uncertain than others, and this uncertainty is mainly caused by difficulty of measuring forest globally [45].

These are the two reasons, especially the first of those listed, why scientific production on the topic analyzed has only increased significantly during the last five years. This could elucidate the relatively modest count of indexed Scopus documents found during the 2004-2022 period (412 documents, also considering conference papers). Concurrently, it is vital to acknowledge that citations not only require time to accrue but also persist in accumulating over time [46]. Indeed, certain studies have asserted that documents necessitate a minimum of two to three years post-

publication to amass sufficient citations, ensuring the reliability of bibliometric indicators [47,48]. Under this perspective, the pioneering nations in this domain, namely the United States and China with 8377 and 1788 accumulated citations, respectively, along with a select few institutions such as the University of Maryland and NASA Goddard Space Flight Center in the United States, the Chinese Academy of Sciences in China, and CIRAD in France, are poised to constitute the core of this topic for the foreseeable future.

What can we expect in the coming years? There has been a noticeable and escalating recognition in the 21st century regarding the environmental consequences linked to deforestation and biodiversity degradation. Moreover, there is an urgent need to comprehend the impacts of climate change attributed to the expanding global population and evolving consumption patterns. [49]. In this context, carbon sequestration, a pivotal element in the climate equation, will assume a significant role in mitigating pollution and gauging an area's capacity to generate biomass. Given the costliness and inefficiency of traditional approaches for creating inventories of production units through in-situ studies (ground-monitoring), there is a shift toward semi-automatic methods utilizing machine learning and deep learning approaches. These methods leverage geo-referenced digital information often extracted from the expanding realm of satellite imagery [50,51]. In this way, the new generation of space-borne LiDAR sensors, in addition to ICESat-2 and GEDI, will notably contribute to expanding the current capabilities to map and monitor forest systems at very large scales.

Within this new generation of space-borne LiDAR sensors, three relevant programs stand out due to their great potential. This is the case of the Terrestrial Ecosystem Carbon Monitoring Satellite, launched in August 2002, which is the first Chinese satellite focused mainly on the forestry sector. It is equipped with a multi-beam pulse LiDAR (25-30 m footprint and 250 m along-track spacing) and high-resolution multi-angle multispectral cameras to estimate canopy height and AGB [52]. The second sensor to take into account in the coming years would be the Multi-footprint Observation LiDAR and Imager (MOLI; Japan Aerospace Exploration Agency). It will mark the inaugural forest observation system to concurrently employ LiDAR and an imager, enabling multiple footprint observations simultaneously. This sensor will be installed aboard the International Space Station and will consist of a 1064 nm dual-beam LiDAR with a pulse repetition frequency of 150 Hz for yielding two parallel paths separated by 50 m on the ground and footprints of 25 m at 50 m intervals along-track [53]. Note that it is possible to measure the slope angle by analyzing triangular triplets of footprints to correct canopy height and ground elevation errors due to slope. Previous simulations in the MOLI system have expected to obtain estimates of canopy height with an error of ± 3 m (canopy height less than 15 m) and a relative error of $\pm 20\%$ (canopy height greater than 15 m). In the same way, AGB will be estimated with an error of ± 25 t/ha (AGB below 100 t/ha) and $\pm 25\%$ relative error (AGB above 100 t/ha) [53]. Finally, the LiDAR Surface Topography (LIST; NASA), which is scheduled to launch in 2025, will mount a very powerful photon counting detection system with 1000 beams to achieve footprints of 5 m in diameter separated by about 0.7 m on the ground (swath mapping). This system will allow obtaining accurate and global topographic information of 5 m grid size and surface elevation changes of forests, lakes, and ice caps [54].

In the last years, there has been a discernible shift towards research endeavors focused on integrating data from diverse satellite remote sensors (optical imagery, SAR, LiDAR, and hyperspectral). Indeed, there is a clear synergy between different sources of remote sensing data. Optical data offers valuable insights into vegetation status, while SAR excels in all-weather conditions, providing details on the physical structure of vegetation. Meanwhile, LiDAR furnishes accurate elevation data without encountering the saturation issues that optical images and SAR data show in heavily vegetated areas and tall canopies. This kind of multi-sensor synergistic approaches can effectively predict the forest canopy height and AGB [55]. This line of spatial data fusion research, coupled with the increasing use of deep learning algorithms in which optical and SAR data play the role of predictors and height measurements from spatial LiDAR sensors serve as calibration data (e.g. [56]), will likely boost large-scale forest monitoring in the coming years.

5. Conclusions

The results obtained in this bibliometric analysis showed that the scientific communications selected from the Scopus database on the topic analyzed were mostly published in the format of articles (73.5%) and conference papers (22.8%), which is the usual way of disseminating scientific knowledge in well-established research disciplines. The number of documents per year increased exponentially, especially in the last five years in which both ICESat-2 and GEDI sensor have been gathering data. Indeed, a substantial portion of the publications (51.45%) emerged within the most recent four years (2019-2022), with the peak volume occurring in 2022 (19.90%). This indicates that the entry into service of the new generation of the space-borne LiDAR sensors (TECM, MOLI, LIST), which incorporate improved technology for capturing high-resolution LiDAR data, will facilitate the emergence of new methods and approaches for large-scale forest mapping.

The main subject categories were Earth and Planetary Sciences (44.6%), Agricultural and Biological Sciences (14.6%) and Computer Science (12.0%), with a clear trend at the end of the study period where the category Earth and Planetary Sciences stands out as the predominant category.

Regarding the scientific impact of the journals involved in the dissemination of knowledge about this field during the period 2004-2022, "Remote Sensing of Environment" turned out to be the journal with the highest total number of citations (4444 citations), followed at a great distance by "Remote sensing" (1454) and "International Journal of Remote Sensing" (633). Similarly, "Remote Sensing of Environment" and "International Journal of Remote Sensing" emerged as the journals contributing significantly to the discussed subject, displaying the highest citation rates per published article (61.7 and 48.7 citations/article, respectively). Notably, the journal "Remote Sensing" led in terms of document output, publishing up to 90 articles.

Regarding the most productive countries, The United States took the lead in document production, with the University of Maryland, College Park, emerging as the foremost research institution in this area, highlighting notable collaborations with various Chinese institutions. In this way, the primary global hubs for collaborative research were the United States, China, and France, forming the three major clusters in the production of research. It should be noted that high-resolution space-borne LiDAR Earth observation has proven to be a cutting-edge engineering research direction internationally, and the United States, primarily through NASA programs, has in recent years led the way in the research content and direction of development of future Earth observation. In any case, China and Japan are also developing sensors (TECM and MOLI), which will contribute to them probably sharing the lead with the United States in the coming years.

In summary, the increasing number of publications from 2004 to 2022 indicates that the subject under study can be classified as a trending research topic, garnering growing interest on a global scale due to the urgent need to collect accurate, timely and large-scale information related to AGB and carbon stocks fixed by forests. The extensive monitoring is deemed crucial within the United Nations Framework Convention on Climate Change strategy, specifically in the context of Reducing Emissions from Deforestation and Forest Degradation. The escalating need for data on the distribution and temporal dynamics of carbon sequestration in forests, crucial for estimating climate change impacts, is likely to propel further research in this direction in the upcoming years.

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Data Availability Statement: The searched period on the analyzed topic during the period 2004–2022 yielded 412 documents (Scopus database). These documents can be accessed in RIS and BIB format at this [link](#).

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