

The economics of Forest Carbon Sequestration: A Bibliometric Analysis

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Research Article

Keywords: Bibliometric analysis, Biblioshiny, Climate change, Economic analysis, Forest Carbon sequestration, Vosviewer

Posted Date: January 13th, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-1236338/v2>

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Abstract

Carbon sequestration in forests has increasingly captured the attention of scientists as a strategy for climate change mitigation and environmental sustainability. In this era of huge carbon emission, being a low-carbon and cost-effective technology, the economic analysis of forest carbon sequestration holds higher importance for the successful implementation and intended outcomes. This study elucidates a scientometric view of the research structure and thematic evolution of economic studies on forest carbon sequestration based on 1,439 articles over the time slice 2001-2021. The bibliographic data has been retrieved from the Dimensions database which accommodates a large coverage of research publications and also provides easy access to essential scholarly data and information. Vosviewer and Biblioshiny software tools have opted for visualization and evaluation purposes of bibliometric data. This study employs various measures of bibliometric analysis like co-authorship, bibliographic coupling, citation and keyword analysis to find out the principal articles, authors, journals, most frequent keywords and highest publishing countries and institutions in this field and the results show that the number of publications has escalated substantially in the last five years, Popp A, 2017 (305 citations) and André P C Faaij (11 documents) are the most cited article and the most productive author, respectively, Bradford's law calculates 21 core journals out of total 503 journals among which *Forest Policy and Economics* is on the top, and the most productive country and institution are the USA and University of Florida, respectively. The study also investigates key publishing subject categories and the number of publications covered under each Sustainable Development Goals. The overall outcome of this bibliometric study confers an in-depth understanding of the various dimensions of economic analysis on forest carbon sequestration, its development pattern in the last 20 years and also provides emerging themes for future references.

1. Introduction

In this era, unsustainable rapid development has caused enormous exploitation of natural scarce resources that are about to exhaust (Nejadi and Rahbar 2012) and has also created the issues like climate change and global warming by releasing a huge amount of carbon into the atmosphere (Sedjo and Sohngen 2012). Such distortion of the ecosystem and its services has negatively affected the economic capacity for sustainable development (Islam and Siwar 2010; Chandra et al. 2011; Nejadi and Rahbar 2012). Therefore, in recent decades, identifying the appropriate land use with good carrying capacity (Al-Mashreki et al. 2010; Aticho and Elias 2011; Nejadi and Rahbar 2012) along with suitable and nature-based solutions for climate change mitigation (Griscom et al. 2017; Koh et al. 2021) has been the prime concern of decision-makers. Forests are one of the most valuable natural resources that fight against climate change (Pache et al. 2021) by potentially reducing atmospheric carbon dioxide with the process of carbon sequestration (Vance 2018; Hou et al. 2019). Forests often act as carbon silos, due to their long life and a large volume of biomass, with net biological growth, offer huge volumes of carbon stored in their cells (Sedjo and Sohngen 2012). In spite of several intangible benefits provided by the forests, the economic quantification of forest services has long been ignored because these values are difficult to measure and are not compatible with the conventional markets (Ninan and Inoue 2013).

The economic analysis of forest services such as carbon sequestration is crucial since it has the considerable economic potential to mitigate climate change (Raihan et al. 2019) and achieve emission reduction targets (Vass and Elofsson 2016). It also provides useful synergies for policymakers to accomplish the targeted objectives with the least net economic and social cost (Sampson and Sedjo 2020). There are a host of studies (De Jong et al. 2000; Ahtikoski et al. 2020; Hussainzad and Mohd Yusof 2020; Sampson and Sedjo 2020; Pache et al. 2021) that have estimated the economic value of forest carbon sequestration and payments for carbon sequestration in forests (Brooke 2009; Cho et al. 2018, 2019). Forest economic policies and incentives can largely influence the process of carbon sequestration (Sedjo and Sohngen 2012) but there are various risks and uncertainties in the assessment of carbon sequestration related to carbon permanence, additionality, and leakage (Obersteiner et al. 2005; Sedjo and Sohngen 2012). There are also some issues associated with the payments for carbon sequestration i. e., choosing a viable reference with respect to which carbon storage is compared, variability across the places and the form taken by payments (Van Kooten and Johnston 2016; Gren and Zeleke 2016; Riviere and Cauria 2021). Regarding the economics of forest carbon sequestration, there is a huge scope of research that could lead to a general consensus on efficient valuation methods and policy instruments to promote it for climate change mitigation.

The current study sought to explore the scientific literature on the “Economics of Forest Carbon Sequestration” (EFCS) by implementing a bibliographic network analysis as there are only a handful of studies that have carried out bibliometric mapping analysis on the economic aspects of forest carbon sequestration. This inference is derived when only 158 articles appeared after searching the keyword query- (“bibliometric analysis” OR “literature review” OR “citation analysis”) AND (“vosviewer” OR “biblioshiny”) AND (“forest” OR “biomass”) AND (“carbon sequestration” OR “carbon capture” OR “carbon sink”) AND (“economics” OR “economy” OR “economic analysis” OR “carbon assessment”)) in the full-text. These 158 articles include bibliometric analysis, literature reviews, meta-analysis, scientometric mapping and cluster/content analysis. Publication fronts of some relevant literature reviews and meta-analyses are related to carbon storage estimation of forest ecosystem, the economics of forest carbon offsets, FCS cost studies, policy design for FCS, economics and policy of carbon sequestration, cost of carbon offsets, and economics of forest ecosystem carbon sinks (Richards and Stokes 2004; Van Kooten et al. 2004; Van Kooten and Sohngen 2007; Bangsund and Leistritz 2008; Van Kooten and Johnston 2016; Gren and Zeleke 2016; Sun and Liu 2020). Further, there are studies (Nardi et al. 2016; Uribe-Toril et al. 2019; Omoregbe et al. 2020; Yu et al. 2020; Wei et al. 2021) that have carried out bibliographic analysis also known as advanced statistic based science mapping by applying various bibliometric units let it be co-authorship, bibliographic coupling, co-citation, and co-occurrence analysis of key authors, documents, sources, references, institutions, countries, and keywords considering various research domains, i.e., payments for ecosystem services, carbon capture technologies for climate change mitigation, trends in carbon offset research, structure and evolution of forest research, etc. But to our knowledge, none of the studies has performed the bibliometric analysis on economics of forest carbon sequestration. The main aim of the present study is to demonstrate the structural evolution and dynamic demeanour of scientific research in this field by projecting the principle and relevant themes, documents, authors, journals,

disciplines, countries, institutions, and keywords using Vosviewer and Biblioshiny software tools and Dimensions database over the period 2001 to 2021. This study will provide significant information to the scholars who want to have a scientific overview of the multidimensional structure, trend pattern, fore and future fronts of researches under the current field of study.

2. Research Methodology

2.1 Bibliometric analysis methods

Bibliometric analysis, as one of the most rigorous practices, has been widely recognised for analysing the various aspects of published academic materials, including highly-cited documents, most influential journals, countries, organizations, and to show a past and present structure of the concerned field through citation, co-authorship, bibliographic coupling, keyword occurrences and cluster analysis (Zhang and Yuan 2019). This approach adopts three main bibliometric indicators to measure scientific development: quantitative indicators (measure the productivity); qualitative indicators (measure the performance); and structural indicators (assess evolution and trend patterns of scientific literature) (Biancolillo et al. 2020). There are several other reasons that attract researchers to adopt this method like research studies integrated with data is more relevant and scientific than the subjective assessment (Nobanee et al. 2021), statistical and mathematical techniques are used to evaluate and predict the research status (Osareh 1996), and this technique guides in acquiring scientific review overviews (van Eck and Waltman 2017).

2.2 Research software

There are numerous bibliometric software tools like CiteNetExplorer (van Eck and Waltman 2014), VOSviewer (van Eck and Waltman 2010), CiteSpace (Chen 2006), BibExcel (Persson, O., R. Danell 2009), and Biblioshiny (Aria and Cuccurullo 2017). Among them, VOSviewer (version 1.6.16, released on 25/Nov/2020) and Biblioshiny (Bibliometrix R tool, version 3.1.3, released on 25/May/2021) software have been incorporated in this study. VOSviewer software is a free Java application used for the creation, visualisation and evaluation of maps obtained from bibliometric data (Aria and Cuccurullo 2017). The new version of VOSviewer supports bibliometric data from Dimensions along with Web of Science, SCOPUS, and PubMed databases (www.vosviewer.com). On the other hand, the Biblioshiny app for bibliometrix redirects users to a web interface to perform visualization and bibliometric analysis without having any knowledge of coding (Aria and Cuccurullo 2017). The Biblioshiny app starts after installing the bibliometrix package (`install.packages("bibliometrix")`) in R Studio and running the `biblioshiny ()` command in R Console (Waghmare 2021). Bibliometrix package applies to many bibliographic data from various databases like Web of Science, SCOPUS, Dimensions.ai, PubMed, and Cochrane (www.bibliometrix.org).

2.3 Data collection

This study has extracted bibliometric data from the Dimensions database, launched by the Digital Science Company in 2018 which have provided a new potential source of scholarly data as proved by many studies (Badke 2018; Orduña-Malea and Delgado López-Cózar 2018; Thelwall 2018; Martín-Martín et al. 2021). This innovative database re-imagines discovery and easy access to research materials by covering 119 million publications contextualized with more than 1.4 billion citations, policy documents, grants, clinical trials, linked patents and Altmetric attention openly accessible to users at app.dimensions.ai (www.dimensions.ai). An interesting feature of this bibliometric data source is the inclusion of new category filters based on 17 SDGs of the United Nations that has been incorporated in this study (Jackson 2020). All these features of Dimensions provide insights to explore new bibliographic ideas.

The retrieved research data were exported in .csv file format applying search criteria (keywords string: ("carbon sequestration" OR "carbon capture" OR "carbon sink" OR "carbon stock") AND ("forest" OR "forestry" OR "biomass") AND ("economics" OR "economic analysis" OR "economic valuation" OR "economic assessment" OR "carbon assessment" OR "carbon valuation" OR "opportunity cost" OR "carbon tax" OR "cost and benefit" OR "carbon pricing")) in Title and abstract (1,802 publications); Limit to articles (1,486 publications); Limit year from 2001 to 2021 (1,439 publications)) on 27th August, 2021. The terms used in the search query were observed by the authors of the present study while reviewing the various set of literature on EFCS.

2.4 Research workflow

[See figure 1]

3. Data Analysis And Results

3.1 Main information and publication trend analysis

The basic bibliometric details on Economics of Forest Carbon Sequestration (EFCS), obtained from biblioshiny application, are presented in Table 1. There are 1,439 publications from 503 sources within the period 2001-2021. Average citations per article and average citations per year per document are 28.57 and 3.733 respectively. The total number of authors is 5,258 and references is 38,388. Authors per Documents index (3.65) is calculated as the total number of authors divided by the total documents. The Co-Authors per Document index (4.47) is the average number of co-authors per document. This index considers the author appearances whereas “authors per documents” counts an author only once, even if he is the author of more than one documents. That is why Authors per Document \leq Co-Authors per Document. The Author Collaboration Index (3.97) is obtained as the ratio of the Authors of Multi-Authored Documents and Total Multi-Authored Documents (Elango and Rajendran 2012). In a sense, the Collaboration Index (CI) is a co-author per documents index obtained by only taking the multi-authored document set (www.bibliometrix.org).

The evolution of annual scientific production is shown in Fig. 2. On average 68.52 peer-reviewed articles on EFCS (SD = 48.82; Median = 69) have been produced each year during (2001-2021) where the minimum number of articles counts for 12 and maximum for 169 in total 1,439 publications. During 2001-2014 (567 total documents), published articles are less than a hundred per year with an average publication of 40.5 per year (SD = 26.37; Median = 30.5; Minimum = 12; Maximum = 89). From 2015-2021 (872 total articles), the number of publications has crossed a hundred documents per year with an average publication of 124.57 per year (SD = 30.70; Median = 114). In 2016 and 2017, the number of articles has slightly fallen to 94 and 92 respectively otherwise there is a rapid increase in publications in the following years. The year 2020 has been the most productive in terms of article publications (169).

Table 1 Main information about bibliometric data of the study

Description	Results
Timespan	2001:2021
Sources (Journals, Books, etc)	503
Documents	1439
Average citations per document	28.57
Average citations per year per doc	3.733
References	38388
DOCUMENT TYPES	
article	1439
AUTHORS	
Authors	5258
Author Appearances	6427
Authors of single-authored documents	131
Authors of multi-authored documents	5127
AUTHORS COLLABORATION	
Single-authored documents	142
Authors per Document	3.65
Co-Authors per Documents	4.47
Collaboration Index	3.97

3.2 Number of publications in the top 10 categories of disciplines and SDGs

The number of publications has been assigned to the top 10 subject categories and Sustainable Development Goals within Fig. 3 in panels (a) and (b), respectively. In panel (a), the top 3 subject categories are Environmental Sciences (510 publications), Agricultural & Veterinary Sciences (422), and Biological Sciences (311) for obvious rationales as forests have ever been an interesting and significant part of natural sciences disciplines. But in recent times, techno-economic analysis of forest biomass for carbon capture and sequestration (CCS) is catching the attention of environmental scientists because the

biomass use and CCS combination results in net negative carbon emission (Yang et al. 2021). The techno-economic assessment under the current field of study helps to discover the technological efficient and economically viable method for climate change mitigation. Such kinds of studies are carried out in the disciplines like Engineering (266 publications) and Economics (233 publications). Studies in Human Society and Earth Sciences also have significant contributions in this field followed by Built Environment & Design, Chemical Sciences, and Technology.

Panel (b) shows that SDG13: Climate Action has the largest number of documents (622 publications) that aims to “take urgent action to combat climate change and its impacts” (www.globalgoals.org). Such a huge number of publications under this category proves the importance of forests for combating climate change. 396 documents have been produced under SDG 7: Affordable and Clean Energy which main aim is to “ensure access to affordable, reliable, sustainable and modern energy for all” (www.globalgoals.org). SDG 15: Life on Land has 262 documents that aim to “protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt biodiversity loss” (www.globalgoals.org). SDG 1: No Poverty; SDG 12: Responsible Consumption and Production; SDG 2: Zero Hunger have also significantly contributed in this field followed by SDG 11, SDG 10, SDG 6, and SDG 8.

3.3 Documents bibliographic coupling analysis and top-cited articles

A network map of documents bibliographic coupling based on citations is generated through VOSviewer software in Fig. 4, showing the most influential works of the highest citation. Of 1,439 publications, 908 meet the threshold while keeping the minimum number of citations to 5. Out of which 100 documents with the greatest total link strength are selected for the study, where the whole combined total link strength is 2785. According to Kessler (1963), bibliographic coupling occurs when two articles refer to common references. Two scholarly works are said to be more intellectually co-related when they have a large number of references in common indicated by a higher numerical value of link strength in this study. The size and colour of circles differ according to the referred common number of citations among the selected documents.

Cluster analysis determines cluster of objects that belongs to similar subject areas. In fig. 4, five clusters are found based on subject relatedness representing five economic dimensions of studies under EFCS. The first cluster is the largest one having 28 items (red nodes) followed by 23 items in the second cluster (green nodes), 20 items in the third cluster (blue nodes), 11 items in the fourth cluster (yellow nodes), and 6 items in the fifth and smallest cluster (purple nodes). The assigned cluster names with their corresponding studies of highest citations along with their research fronts are shown in Table 2. Only those studies are included in each cluster that are relevant to the cluster themes. Cluster 1 is made of the studies related to the economics of forest carbon sequestration (FCS) mainly contributed by Corbera (2007) – 240 citations, Van Kooten (2004) – 101 citations, Mckenney (2004) – 56 citations, Stainback (2002) – 53 citations, Boyland (2006) – 35 citations, Slaney (2009) – 9 citations, and Lintunen (2016) – 8 citations. Cluster 2 includes topics confronting to the economic assessment of FCS mainly conducted

by Liu (2014) – 63 citations, Triviño (2015) – 55 citations, Rodríguez-veiga (2017) – 42 citations, De Koning (2005) – 33 citations, Pelletier (2012) – 27 citations and Chu (2019) – 23 citations. Cluster 3 corresponds to the socio-economic scenario of FCS, main studies are carried out by Swetnam (2010) – 188 citations, Drescher (2016) – 140 citations, Samii (2014a, 2014b) – 68, 25 citations, Bluffstone (2013) – 39 citations, and Djanibekov (2014) – 23 citations. The fourth cluster is about the environmental and economic impact of land-use systems, studies are mainly performed by Popp (2017) – 320 citations, Daioglou (2019) – 57 citations, and Brandão (2010) – 31 citations. The fifth cluster is based on the economic viability of FCS, main works are done by Jerath (2016) – 53 citations and Thompson (2014) – 49 citations.

Table 2 Summary of total 5 clusters of Documents bibliographic coupling

Clusters	Studies with the highest citations	TC	Research fronts
1. Economics of forest carbon sequestration (FCS)	Corbera (2007) DOI: 10.1111/j.1467-7660.2007.00425.x	188	Equity and legitimacy of markets for ecosystem services
	Van Kooten (2004) DOI: 10.1016/j.envsci.2004.05.006	115	How costly are carbon offsets?
	Mckenney (2004) DOI: 10.1016/j.forpol.2004.03.010	66	Cost estimates for carbon sequestration
	Stainback (2002) DOI: 10.1078/1104-6899-00006	61	Economic analysis of slash pine FCS
	Boyland (2006) DOI: 10.1139/x06-094	35	The economics of using forests for carbon storage
	Slaney (2009) DOI: 10.1016/j.forpol.2009.07.009	15	The economics of carbon sequestration through pest management
2. Economic assessment of FCS	Lintunen (2016) DOI: 10.1016/j.jfe.2016.05.001	8	Economics of forests and climate change
	Liu (2014) DOI: 10.1007/s10980-014-0081-4	63	Grain to Green Program for FCS
	Triviño (2015) DOI: 10.1016/j.ecoser.2015.02.003	55	Managing boreal forest with economic investment for FCS
	Rodríguez-veiga (2017) DOI: 10.1007/s40725-017-0052-5	42	Quantification of forest carbon stocks
	De Koning (2005) DOI: 10.1579/0044-7447-34.3.224	33	Assessment of ecological and economic potential of FCS
	Pelletier (2012) DOI: 10.1016/j.forpol.2010.05.005	27	Economic assessment of forest carbon stocks uncertainties
	Chu (2019) DOI: 10.1016/j.jclepro.2018.12.296	23	Economic assessment of FCS
	3. Socio-economic scenario of FCS	Swetnam (2010) DOI: 10.1016/j.jenvman.2010.09.007	196
Drescher (2016) DOI: 10.1098/rstb.2015.0275		122	Socio-economic functions of tropical

	Samii (2014a, 2014b) DOI: 10.4073/csr.2014.11, DOI: 10.4073/csr.2014.10	27, 12	land use Effects of FCS on poverty in low- and middle-income countries
	Bluffstone (2013) DOI: 10.1016/j.ecolecon.2012.12.004	38	REDD+ for low-income countries
	Djanibekov (2014) DOI: 10.1007/s10640-014-9843-3	22	Stochastic economic assessment of afforestation
4. Environmental and economic impact of land- use systems	Popp (2017) DOI: 10.1016/i.gloenvcha.2016.10.002	305	Land-use futures in the shared socio- economic pathways
	Daioglou (2019) DOI: 10.1016/j.gloenvcha.2018.11.012	59	Integrated assessment of biomass supply and demand
	Brandão (2010) DOI: 10.3390/su2123747	34	Environmental and economic impacts of multifunctional land- use systems
5. Economic viability of FCS	Jerath (2016) DOI: 10.1016/j.envsci.2016.09.005	51	Role of economic, policy, and ecological factors in carbon stock estimation
	Thompson (2014) DOI: 10.1016/j.ecoser.2014.03.004	46	The economic viability of blue carbon

TC: Total Citations

Out of the most cited articles on the economics of forest carbon sequestration, the top 10 studies shorted by relevance as per the theme of the current study have been selected and shown in Table 3 along with their digital object identifier (DOI) number. The article POPP A (2017) entitled “Land-use futures in the shared socio-economic pathways” is the highly cited document with 305 citations followed by RICHARDS KR (2004)’s “A review of forest carbon sequestration cost studies: A dozen years of research” with 252 citations, SWETNAM R (2010)’s “Mapping socio-economic scenarios of land cover change: A GIS method to enable ecosystem service modelling” with 196 citations, CORBERA E (2007)’s “The Equity and Legitimacy of Markets for Ecosystem Services” with 188 citations, and RHODES JS (2005)’s “Engineering economic analysis of biomass IGCC with carbon capture and storage” with 136 citations. The remaining five significant studies are DRESCHER J (2016), VAN KOOTEN (2004), BARR CM (2012), GOLUB A (2009), KURGANOVA I (2014).

Table 3 Top 10 highly cited research articles sorted by relevance

Paper	Title	TC
POPP A, 2017 DOI: 10.1016/i.gloenvcha.2016.10.002	Land-use futures in the shared socio-economic pathways	305
RICHARDS KR, 2004 DOI: 10.1023/B:CLIM.0000018503.10080.89	A review of forest carbon sequestration cost studies: A dozen years of research	252
SWETNAM R, 2010 DOI: 10.1016/j.jenvman.2010.09.007	Mapping socio-economic scenarios of land cover change: A GIS method to enable ecosystem service modelling	196
CORBERA E, 2007 DOI: 10.1111/j.1467-7660.2007.00425.x	The equity and legitimacy of markets for ecosystem services	188
RHODES JS, 2005 DOI: 10.1016/J.BIOMBIOE.2005.06.007	Engineering economic analysis of biomass IGCC with carbon capture and storage	136
DRESCHER J, 2016 DOI: 10.1098/rstb.2015.0275	Ecological and socio-economic functions across tropical land-use systems after rainforest conversion	122
VAN KOOTEN, 2004 DOI: 10.1016/j.envsci.2004.05.006	How costly are carbon offsets? A meta-analysis of carbon forest sinks	115
BARR CM, 2012 DOI: 10.1016/J.BIOCON.2012.03.020	The political economy of reforestation and forest restoration in Asia-Pacific: Critical issues for REDD+	97
GOLUB A, 2009 DOI: 10.1016/j.reseneeco.2009.04.007	The opportunity cost of land use and the global potential for greenhouse gas mitigation in agriculture and forestry	89
KURGANOVA I, 2014 DOI: 10.1111/gcb.12379	Carbon cost of collective farming collapse in Russia	77

TC: Total Citations

3.4 Highly cited and most productive authors

The VOSviewer citation map of the most influential authors extracted from the Dimensions bibliometric database is represented in Fig. 5. From the 5,250 total authors, the top 100 highly cited authors have been selected for the analysis, out of which 34 researchers met the threshold according to the relatedness of their number of co-authored publications. The graph is demonstrating 6 clusters and 116 total co-authorship links. The most cited author in each cluster representing the name of that cluster. For instance, cluster 1 is represented by Hertel, Dietrich having 567 citations. In the same way, cluster 2 is represented by Obersteiner, Michael securing 744 citations followed by Kriegler, Elmer with 402 citations, Popp,

Alexander with 525 citations, Calvin, Katherine V with 1,305 citations, and Faaij, André P C with 644 citations. It is remarkable to observe from the map that no clusters have any overlap, evidencing relative independence of research groups under EFCS.

Table 4 reveals the list of the top 10 most active authors shorted by the number of documents produced by them. The table provides information about the author's citations, affiliations, and the title of one of the articles produced by the respective author which is closely related to the research agenda of the present study along with their DOIs. The highest documents are published by André P C Faaij (11 documents), followed by Pete, Smith (9 documents), Bren L Sohngen (8 documents), Michael Obersteiner and Timo Pukkala (7 documents), Mohamed Pourkashanian and Daniel W Mckenney (6 documents), Jiamen Ge and Indu K Murthy (5 documents), and Gerrit Cornelis Van Kooten (4 documents).

Table 4 Top 10 most productive authors

Authors	Doc	TC	Title of one of the studies produced by the corresponding author with DOI	Affiliations
André P C Faaij	11	644	Forestry projects under the Clean Development Mechanism? DOI: 10.1023/A:1026370624352	University of Groningen, Netherlands
Pete Smith	9	779	The Technological and economic prospects for CO ₂ utilization and removal DOI: 10.1038/S41586-019-1681-6	University of Aberdeen, United Kingdom
Brent L Sohngen	8	338	The opportunity cost of land use and the global potential for greenhouse gas mitigation in agriculture and forestry DOI: 10.1016/J.RESENEECO.2009.04.007	The Ohio State University, United States
Michael Obersteiner	7	744	Site identification for carbon sequestration in Latin America: A grid-based economic approach DOI: 10.1016/j.forpol.2004.12.003	International Institute for Applied Systems Analysis, Austria
Timo Pukkala	7	106	At what carbon price forest cutting should stop? DOI: 10.1007/S11676-020-01101-1	University of Eastern Finland, Finland
Mohamed Pourkashanian	6	1,332	Techno-economic and environmental assessment of BECCS in fuel generation for FT-Fuel, BIOSNG and OME X DOI: 10.1016/J.RSER.2009.06.001	University of Sheffield, United Kingdom
Daniel W Mckenney	6	141	Cost estimates for carbon sequestration from fast growing poplar plantations in Canada DOI: 10.1016/j.forpol.2004.03.010	Natural Resources Canada, Canada
Jiamen Ge	5	40	Carbon sinks and output of China's forestry sector: An ecological economic development perspective DOI: 10.1016/j.scitotenv.2018.11.219	Xiamen University, China
Indu K Murthy	5	49	Carbon forestry economic mitigation potential in India, by land classification DOI: 10.1007/s11027-006-9063-4	Indian Institute of Science Bangalore, India
Gerrit Cornelis Van Kooten	4	199	Economics of Forest Ecosystem Carbon Sinks: A Review DOI: 10.1561/101.00000006	University of Victoria, Canada

Doc: Number of documents, TC: Total citations

3.5 Citations analysis of Core Journals and Bradford's Law

From the analysis of subject categories and cluster analysis of articles, it is observed that studies on EFCS have multidisciplinary features and cover a wide range of research themes that have been published in a variety of journals with various research orientations. The source-citation analysis of core journals has been performed to understand the significance and collaboration of each specific journal in creating the knowledge on EFCS. Journal density visualization map based on documents-weights is prepared through VOSviewer shown in Fig. 7. Of the 503 sources, producing 1,439 documents, 65 meet the thresholds keeping the minimum number of documents of a source to 5 and the minimum number of citations of a source to 5. The largest set of connected items are consist of 63 items. The colour schemes of the source density visualization map is of Rainbow type varying from red, yellow, green to blue colour where red corresponds to the highest document density and blue corresponds to the lowest document density. In other words, the colour of each node in the density visualization plat depends on the density of that node.

In this way, the density visualization pattern helps to understand the whole structure of the map by concentrating on the most relevant areas in the map. Hence, we can trace the most productive journals instinctively on the map. From Fig. 6, Forest policy and economics, Forest ecology and management, Forests, Journal of cleaner production and Journal of environmental management represent the core and most productive five sources in the current field of study. The top 10 leading journals with their frequencies, citations, H index, and start year are shown in Table 5. The frequencies of the top 5 journals are 50, 41, 34, 32, and 29 respectively. Forest ecology and management has the highest citation count (1782) and The science of the total environment has the highest H index (244), both journals have started in the year 2002 and 2016 respectively. On the other side, Forests has the lowest citation (312) and lowest H index (44), which started in the year 2010.

Table 5 List of top 10 most productive journals

Sources	Frequency	Citations	H index	Start year
FOREST POLICY AND ECONOMICS	50	955	68	2001
FOREST ECOLOGY AND MANAGEMENT	41	1782	176	2002
FORESTS	34	312	44	2010
JOURNAL OF CLEANER PRODUCTION	32	722	200	2009
JOURNAL OF ENVIRONMENTAL MANAGEMENT	29	1235	179	2003
THE SCIENCE OF THE TOTAL ENVIRONMENT	29	830	244	2016
APPLIED ENERGY	23	590	212	2013
MITIGATION AND ADAPTATION STRATEGIES FOR GLOBAL CHANGE	22	406	71	2001
ENVIRONMENTAL SCIENCE AND POLICY	19	978	115	2003
ECOLOGICAL ECONOMICS	18	828	202	2001

Table 6 Zone wise distribution of journals

Zones	Total Journals (503)	Journal Percentage	Total articles (1,439)	Article Percentage
Zone 1	21	4.17%	486	33.77%
Zone 2	94	18.68%	480	33.35%
Zone 3	388	77.14%	473	32.87%

Bradford's law is a distribution pattern discovered by Samuel C. Bradford (1934) to measure the exponentially diminishing returns of reference searches in scholarly journals. Bradford claims that for a given subject field "there are a few very productive periodicals, a larger number of more moderate producers, and a still larger number of constantly diminishing productivity" (Nash-Stewart et al. 2012). Under this law, if scientific journals of a subject are arranged into three groups by the number of articles, each occupying about $1/3^{\text{rd}}$ of total articles, then the proportion of the number of journals in each group will be $1:n:n^2$ (Table 6). These three groups are formally known as Zone 1 or core, Zone 2 or middle part, and Zone 3 or tail. Fig. 7, derived from Biblioshiny app, highlights the Zone 1 or "core journals" that are most frequently cited and the researchers in this field are likely to have more interest in these journals. Zone 2 consists of the journals with average citations. Zone 3 reflects a long tail like picture of those journals that are considered as of marginal importance and very rarely cited (Potter 2010). Table 6 shows that Zone 1 includes 21 "core journals" which is 4.17% of the total 503 journals containing 486 articles. Zone 2 have 94 journals (18.68% of total journals) with 480 articles. Zone 3 have the largest number of less cited journals covering 77.14% of all journals in this discipline, containing 473 articles. From the table, it is clear that each Zone has comprised of one-third of the total articles.

3. 6 Co-authorship analysis of countries and institutions

Regional collaboration, degree of communication, and research hotspots could be identified from the network visualization map of co-authorship occurrences among countries. The overlay visualization map of country co-authorship based on documents-weights in the field of EFCS is represented in Fig. 8. Keeping the minimum number of documents and citations of a country to 5, of the 99 countries 51 meet the thresholds. For each of the 51 countries, the total strength of the co-authorship with other countries is analysed. The size of the frames represents the influential countries according to the number of occurrences of documents. The distance between two nodes reflects the connection of their co-authorship link, and the thickness of the networking lines shows the strength of the link. The colour gradient is shown in the lower right corner of the map indicating the publication year of the author. The colour of the frame of a country is decided by the number of scores where blue represents the lowest score (the oldest or pioneer countries) and yellow represents the highest score (the latest or emerging countries).

The global distribution of documents published on EFCS is illustrated on the world map in Fig. 9 where the white spaces are representing no data. In the map, the colour gradient varies from red (highest publication) to green (lowest publication). Table 6 shows the top 10 countries of highest scientific production with their citations and total link strength (TLS) values. From the overlay map (Fig. 8), world map (Fig. 9) and Table 7, it is understood that the United States (US) is a pioneer country in this field with the highest document production (336), citations (13315) and TLS (264). With such great scores, the US becomes the research centre in the area of EFCS followed by China, which is the central research spot in Asia with 197 documents production and 3329 citations. The US is strongly linked with China having 31 link strengths. Link strength between US and UK is 30 and it is equally connected with Canada, Netherlands, and Germany having 15 link strengths. China is strongly linked with the US, Canada, and Germany. The other main pioneering countries with blue, purple frames are Germany, Netherlands, Canada, Norway, South Africa, Mexico, and Columbia. Iran, Philippines, Pakistan, Belgium, Singapore, Portugal and Greece are the latest emerging countries in this field represented in yellow frames. Out of which Belgium has created strong links with pioneering countries like the US, UK, Netherlands, and Canada in a very short period.

Table 7 Top 10 most productive countries

Country	Documents	Citations	TLS
United States	336	13315	264
China	197	3329	121
United Kingdom	136	6021	172
Australia	99	4806	138
Germany	99	4364	171
Canada	86	3239	90
Netherlands	60	3615	109
India	58	1127	20
Finland	51	1461	59
Spain	48	2832	64

TLS: total link strength

The overlay network map of co-authorship occurrences in institutes based on documents- weights are shown in Fig. 10. Of the 1240 institutes, 133 meet the threshold. Out of which, 100 items are selected for the scientific collaboration analysis of institutes. The top five institutes with the highest documents production are the University of Florida – 22 documents (U. S.), University of Chinese Academy of Sciences – 20 documents (China), Wageningen University & Research – 20 documents (Netherlands), University of British Columbia – 19 documents (Canada), and University of Eastern Finland – 17 documents (Finland). The overlay visualization illustrates that Wageningen University & Research, University of Florida, University of British Columbia, University of Göttingen, and University of East Anglia are the main pioneering organizations whereas Federal University of Rio De J, National University of Singapore, University of Tokyo, Harvard University and Kyoto University are the latest emerging institutes in this field. Among the newest institutes, Harvard University is growing rapidly and has created a good link strength with all kinds of institutes ranging from oldest to the newest.

3.7 Title's Keyword analysis and thematic evolution

The title's keyword analysis analyses the keywords that have been occurring in the title of the articles published in the concerned field. Such kind of investigation is required to establish the research trend, ascertain the research gaps in the studies on EFCS, and discover the interesting fields and themes that need special attention of researchers. Word Cloud is an instrument for representing the word's frequency in terms of occurrences in a text body. This approach visualizes a bunch of words that appear in different font sizes depending on how frequently they have occurred in the source text. This lucrative and effective technique of keyword analysis brings forth an instant result of trendy research fronts.

To create the Word Cloud of keywords, R-Studio based bibliometrix tool- 'Biblioshiny app' is used (Fig. 11). In the Biblioshiny app, under graphical parameters, the field is selected as 'Titles', N-grams is selected as 'Bigrams', and the number of words is selected as '70'. The word occurrence measure is 'Frequency',

shape- 'Cardiod', font type- 'Verdana', and text colour is 'Random Dark'. At last, the Ellipticity and Padding values are selected as 0.65 and 1 respectively. The Treemap of the top 20 most frequent keywords with their frequency and percentage of occurrences are illustrated in Fig. 12. The Word Cloud and Treemap both figures altogether depict that 'carbon sequestration' is the most used keyword with 201 frequency and 21% of occurrence followed by 'climate change', 'ecosystem services', 'carbon stocks', 'carbon capture', 'forest carbon', 'forest management', and 'carbon storage' that have usually occurred 9-4% of the times in the title of the articles, indicating the most highlighted, trendy, and significant part of the field. But at the same time, keywords like 'techno economic', 'economic analysis', 'economic assessment', 'socio-economic', and 'sequestration potential' have retained comparatively less percentage of occurrences that is about 3-2%. This analysis infers a huge research gap in the economic analysis of forest carbon sequestration where themes like carbon sequestration, climate change, and carbon capture are studied in the majority and the economic aspects of this field are lacking attention. However, in recent times, the trend of themes has shuffled as delineated by Sankey diagram of the thematic evolution in Fig.13.

The thematic evolution technique identifies the changing paths of studies, evolutionary relationships as well as structures, contexts, and strength of emerging themes that appear over time. This method plays a very important role in portraying the degree and direction of field development and also in forecasting the trends of the field (Cobo et al. 2011). The Sankey diagram (Fig. 13) displaying thematic evolution is a kind of flow chart where the width of the arrow is proportional to the quantity flow. Each node in Fig. 13 corresponds to a topic and the width of the node is proportional to the frequency of keyword occurred under the theme. A thick node characterizes the relevance of that theme. Three-time zones (2001-2013; 2014-2017; 2018-2021) are wired to illustrate the temporal movement between research topics. This Sankey graph has clearly shown the evolution and extinction of themes related to the current field of study over time. During 2001-2013, almost one decade, the themes like forest carbon sequestration and greenhouse gas emissions were the major part of the study which came on top during 2014-2017. In the time slice (2001-2013), there was no sign of the economic aspects of FCS (forest carbon sequestration) that further emerged for the first time during 2014-2017 but was not on the list of priority. The 'economic analysis' which is the main focus of this study came on top in recent times during 2018-2021, signifying the awareness of researchers in bridging up the research gaps that were identified by the Word Cloud and Treemap analysis of keywords.

4. Limitations Of The Study

This bibliometric literature on the EFCS replicate numerous facets of research achievements in the form of documents, journals, countries, institutions, and keywords analysis, but also suffers from some limitations: 1. The bibliometric data used in this study are only derived from the Dimensions database and does not includes datasets from Web of Science, SCOPUS, PubMed, or other bibliometric sources, 2. This study includes documents published only from 2001 to 2021 and because of that, some influential works published before 2001 have been left from the analysis, 3. Only peer-reviewed articles are considered in the study. It does not include kinds of literature like books, reports, working papers, and

thesis, 4. References analysis is not included because it is not possible to perform all the bibliometric measures in a single study, 5. Many articles fully devoted to the concept of EFCS are missing from the study because the same terminology does not explicitly exist in the titles and abstracts of those articles as used in the keyword search string of the current study, and 6. This study does not perform deeper investigation, for instance, methods/models and the significant outcomes, which need to be further integrated.

5. Discussion, Conclusion And Future Research Recommendation

In this fast-growing complex world, our environment and ecosystem are facing lots of side-effects of rapid and unsustainable development like GHG emissions, heat waves, and climate change. To protect our earth from the climate crisis, targets have been set to limit global warming to well below 2⁰C, preferably to 1.5⁰C, compared to pre-industrial levels. To achieve this target, global and national policymakers are inclined to adopt a low carbon cost-effective technology and forest carbon sequestration (FCS) is one of them. Analysing the economic aspects of FCS is essential for providing incentives to the national governments, landowners, and stakeholders which further helps to achieve green economic growth and sustainable development.

This study proposes a holistic overview of bibliometric analysis on the EFCS based on 1,439 articles from the period 2001 to 2021, by integrating the Dimensions.ai bibliometric data in VOSviewer and Biblioshiny app. This approach is useful to understand the multidimensional nature of the EFCS by observing a tremendous set of literature published in this field. The objective of this study is to produce maps, tables, and graphs of certain units of interest such as documents, authors, subject categories, SDGs, journals, countries, institutions, keywords, and thematic evolution. The results of the analysis, in brief, are: 1. The number of documents published in the field of EFCS has increased mainly after 2015 by surpassing 100 documents per year, 2. Environmental Sciences and SDG 13: Climate Action are the most productive subject category and sustainable development goal respectively, 3. Five clusters are extracted through the cluster analysis of documents bibliographic coupling namely the economics of forest carbon sequestration (FCS), economic assessment of FCS, socio-economic scenario of FCS, environmental and economic impact of land-use systems, and economic viability of FCS, 4. André P C Faaij is the most productive author, 5. POPP A, 2017 has been the most cited article in this field, 6. There are 21 core journals as per Bradford's law out of 503 total journals among which *Forest Policy and Economics* is the most productive journal, 7. The United States, China, and United Kingdom are the most active countries, 8. University of Florida, University of Chinese Academy of Sciences, and Wageningen University & Research are the leading institutions, 9. Carbon sequestration, climate change, and ecosystem services are the most frequent keywords indicating less exposure given to the economic analysis of FCS over the last 20 years, and 10. Thematic analysis reveals that techno-economic analysis, forest carbon sequestration, and GHG emissions are the key evolving areas of research.

Nevertheless, the bibliometric studies specifically related to the economic aspects of FCS are almost negligible, the findings of the current study are consistent with several other existing bibliometric literature

related to forest carbon sequestration, evolution of forest research, carbon capture, and carbon offsets. Many studies (Nardi et al. 2016; Aznar-Sánchez et al. 2018; Uribe-Toril et al. 2019; Nobanee et al. 2021; Wang et al. 2021) have found the similar most frequent keywords like 'Climate Change', 'Ecosystem Services', 'Carbon Sequestration', 'Forest Management', 'Economics', and 'Economic Valuation' as the present study. The main subject categories of this multidisciplinary field are- Environmental Sciences, Agriculture, Biological Sciences, and Economics that is also verified by the following studies (Aznar-Sánchez et al., 2018; Huang et al., 2020; Uribe-Toril et al., 2019; Wang et al., 2021; Wei et al., 2021). Studies like- (Aznar-Sánchez et al., 2018; Huang et al., 2020; Nardi et al., 2016; Nobanee et al., 2021; Wang et al., 2021) have also reported that *Forest Ecology and Management*, *Journal of Cleaner Production*, *Forests*, *Forest Policy and Economics*, and *Ecological Economics* are the leading Journals in this field. A number of studies (Huang et al., 2020; Nobanee et al., 2021; Omoregbe et al., 2020; Uribe-Toril et al., 2019; Wang et al., 2021) have similarly found that the US, UK, China, Germany, Canada, and the Netherlands are the most productive countries. It is consistent with many other documents (Aznar-Sánchez et al., 2018; Huang et al., 2020; Nobanee et al., 2021; Wang et al., 2021) that Chinese Academy of Sciences, Wageningen University & Research, University of Florida, and University of Göttingen are the leading institutions in this field. The outcomes of present and existing literature (Aznar-Sánchez et al. 2018; Wang et al. 2021) put forths a major research gap indicating a deficiency of researches on FCS from economic point of view mainly because the economic estimation of forest services are difficult to measure and are not in line with the conventional markets (Ninan and Inoue 2013). This bibliometric analysis hints that there are a lot of scopes in this field that are yet remained to explore like EFCS under the conditions of risk & uncertainty which paves the direction for future research and it will also render efficacious and valuable information to the practitioners and policymakers.

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Declarations

Declaration of Competing Interest: The authors declare no conflict of interest.

Funding Information: The authors declare that funders have no role in the writing of the manuscript, or in the decision to publish the results.

Author Contributions: P.Verma collected the data, designed the research procedure, performed the data analysis, and wrote the draft manuscript; P.K.Ghosh, the co-first coauthor, supervised, reviewed and edited, and finalized the manuscript. Both the authors have read and agreed to the final version of the manuscript.

Figures

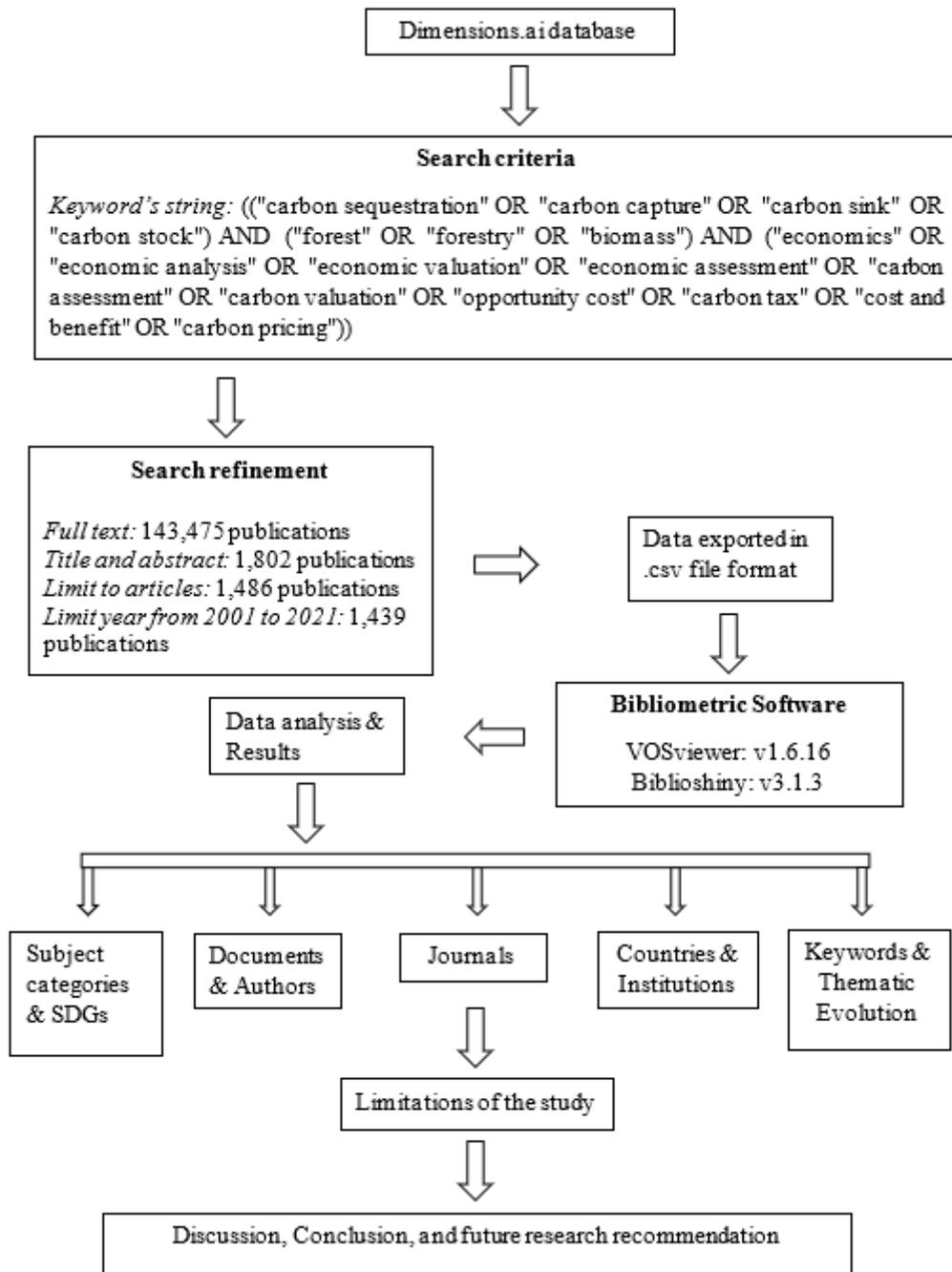


Figure 1

Bibliometric research workflow of the study

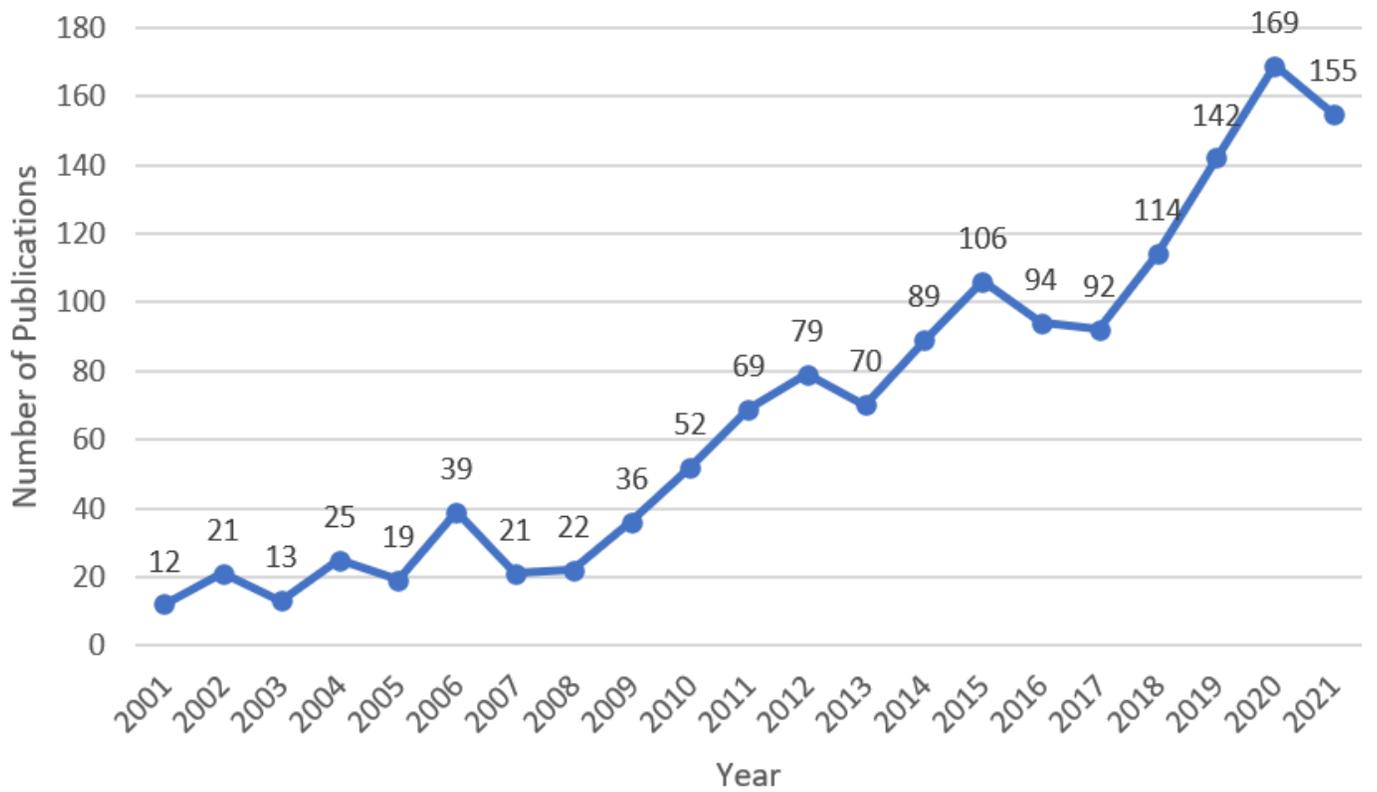


Figure 2

The growth trends of publications from 2001 to 2021

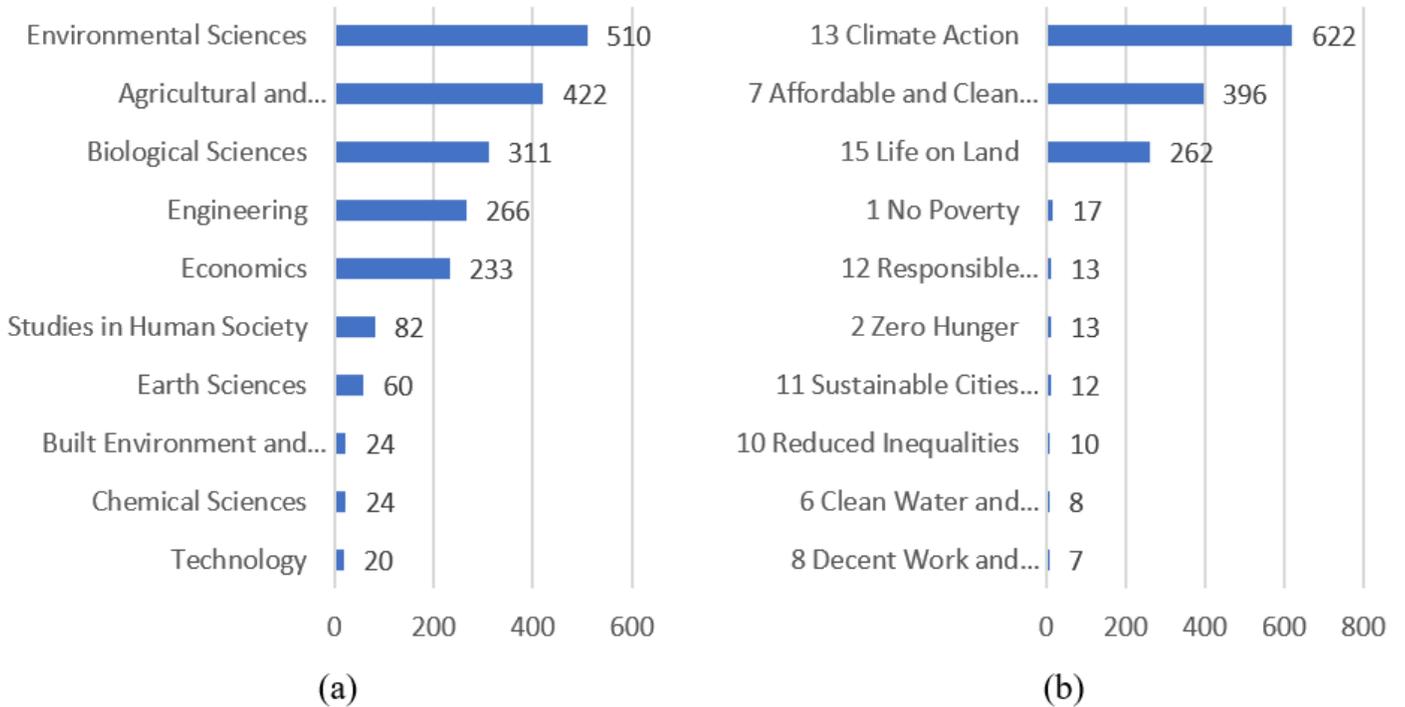


Figure 3

Top 10 subject categories (a) and Sustainable Development Goals (b)

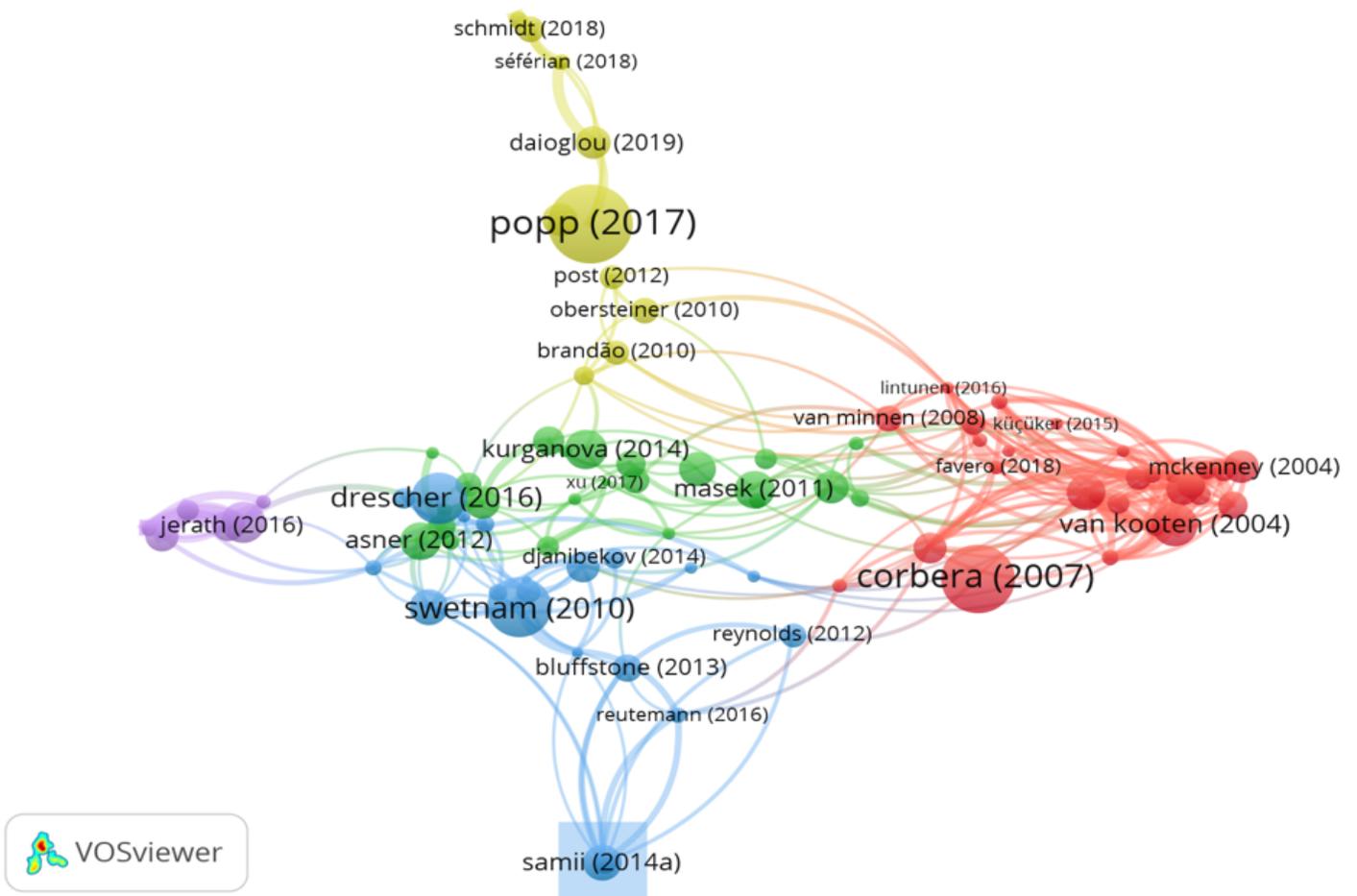


Figure 4

Map of bibliographic coupling of documents based on citations

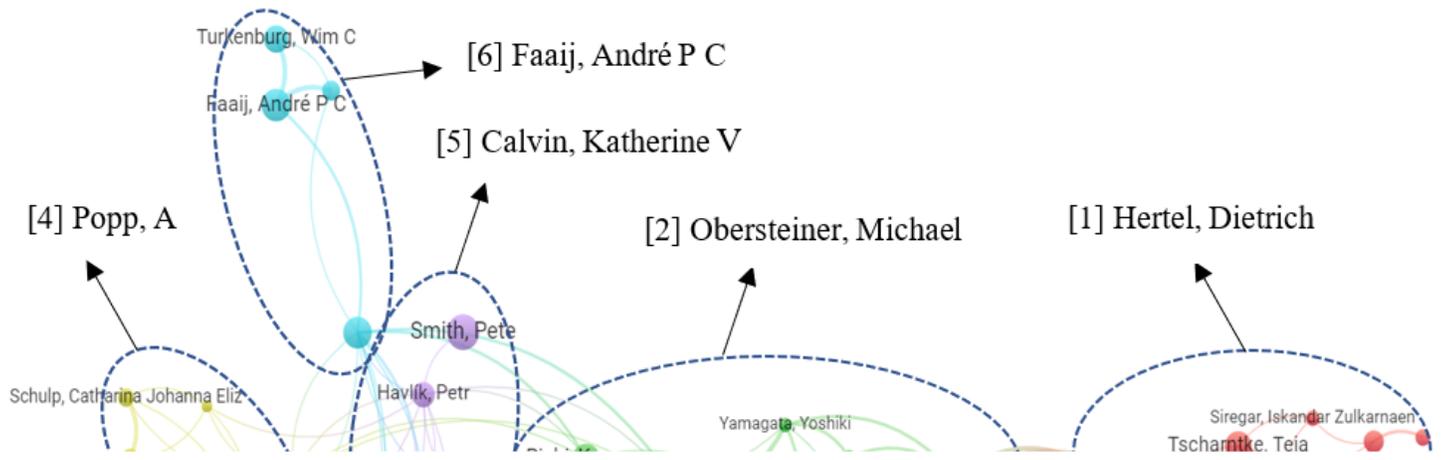


Figure 5

Citation map of prolific authors

Figure 6

Density visualization map of core sources based on number of documents

Bradford's Law

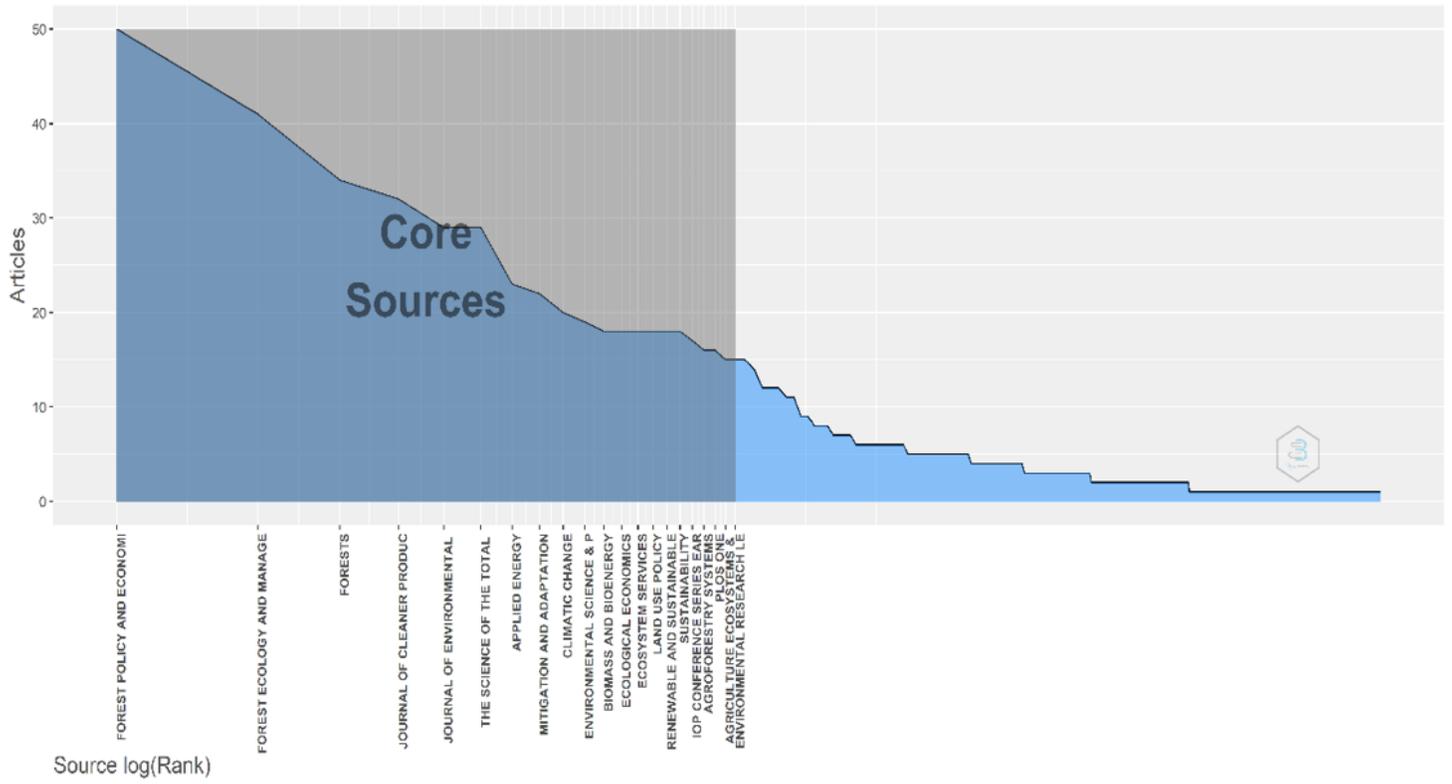


Figure 7

Bradford's Law- highlighting the journals in Zone 1 (core journals)



Figure 8

Overlay visualization map of country co-authorship



Figure 9

Global distribution of documents among countries

Figure 10

Overlay Network Map of Institutes



Figure 11

Word cloud of Title's keyword

Figure 12

Treemap of top 20 Title's keyword with the percentage of occurrences

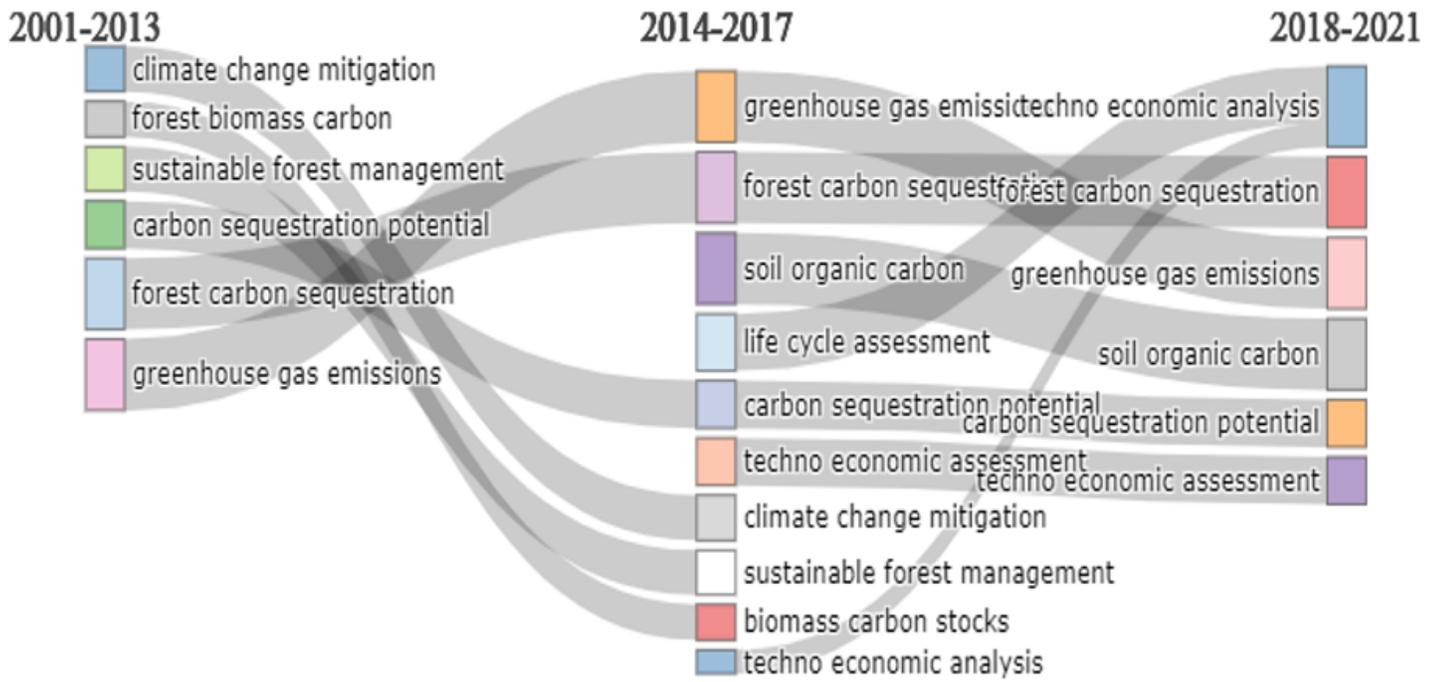


Figure 13

Thematic evolution based on word occurrences