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A research landscape bibliometric analysis on climate change for last decades: Evidence from applications of machine learning ☆

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A R T I C L E I N F O

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A B S T R A C T

Climate change (CC) is one of the greatest threats to human health, safety, and the environment. Given its current and future impacts, numerous studies have employed computational tools (e.g., machine learning, ML) to understand, mitigate, and adapt to CC. Therefore, this paper seeks to comprehensively analyze the research/publications landscape on the MLCC research based on published documents from Scopus. The high productivity and research impact of MLCC has produced highly cited works categorized as science, technology, and engineering to the arts, humanities, and social sciences. The most prolific author is *Shamsuddin Shahid* (based at *Universiti Teknologi Malaysia*), whereas the Chinese Academy of Sciences is the most productive affiliation on MLCC research. The most influential countries are the United States and China, which is attributed to the funding activities of the National Science Foundation and the National Natural Science Foundation of China (NSFC), respectively. Collaboration through co-authorship in high-impact journals such as *Remote Sensing* was also identified as an important factor in the high rate of productivity among the most active stakeholders researching MLCC topics worldwide. Keyword co-occurrence analysis identified four major research hotspots/themes on MLCC research that describe the ML techniques, potential risky sectors, remote sensing, and sustainable development dynamics of CC. In conclusion, the paper finds that MLCC research has a significant

☆ The National Key Research and Development Program of China (NKP) is another major funder of MLCC research worldwide. To date, the NKP has funded a total of 84 publications (1.163 citations, *h*-index = 17) authors by various China- and foreign-based researchers through collaborations. Some notable publications funded by the NKP are Chen et al. [77], Abowarda et al. [78], and Guo et al. [74], which examined ML applications in soil properties, water availability, and phenological and climatic studies in agricultural yield. Other notable funders include the National Aeronautics and Space Administration (NASA, 57 publications) and the Chinese Academy of Sciences (53). Further analysis shows that the funding landscape for MLCC research is mostly dominated by agencies from China and the United States, which accounts for their high productivity, as earlier surmised. The availability of funding in such nations creates research clusters or hotspots [79,80], which in the long term determines the growth and development trajectory of any field of research [81,82]. Section VIII presents an overview of the current research hotspots or themes of MLCC research.

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socio-economic, environmental, and research impact, which points to increased discoveries, publications, and citations in the near future.

1. Introduction

Climate change is described as one of the greatest threats facing humanity in this current age as well as future generations [1,2]. It is also portrayed as a man-made disaster with significant risks to human health, safety, and the environment at large [3]. According to NASA, climate change is a shift in the normal weather or seasonal conditions of any given region over time [4]. It can occur due to natural or man-made (anthropogenic) activities such as fossil fuel combustion which generates and emits greenhouse gases (GHG) such as carbon dioxide and methane. Over time, the accumulation of the GHGs in the earth's atmosphere warms (by increasing average global temperature) thereby transforming weather and environmental conditions [5]. Similarly, the increasing concentration of emitted GHGs decreases the earth's natural carbon reduction sinks which results in the so-called greenhouse effect [6].

Numerous studies have reported that climate change could result in global and unprecedented challenges for humanity. For example, the changes in weather/climatic conditions caused by climate change are anticipated to cause extreme heat waves, acute droughts, and air pollution along with the risk of calamitous flooding [7], which could result in water supply, food insecurity, hunger, and malnutrition [8,9]. Similarly, analysts speculate that climate change could worsen the impacts of pollution and environmental challenges which could pose grave risks to human health, well-being, and safety [10]. According to the World Health Organization (WHO), climate change will severely impact human health in numerous other ways such as disrupting drinking water supplies, nutritional food contents, and safe housing among others [11]. Given its current and potential impacts on humans, ecology, and the environment, global analysts posit that drastic action is required to understand, mitigate, and adapt to climate change to prevent its future catastrophic and costly impacts [7].

Over the years, many strategic policies and transformational measures have been proposed to reduce CO_2 and other GHG emissions and global surface temperatures for better recognition and adaptation to the impacts of climate change [11]. Likewise, sustainable approaches and innovative technologies are currently adopted to predict and understand climate change impacts on various sectors. One such approach is the use of computational methods such as artificial intelligence (AI), the internet of things (IoT), and deep/-machine learning. The unpredictability of climatic conditions requires such advanced computational tools for effective early detection of weather patterns and estimating the impacts of climate change [12]. Therefore, the use of machine learning (ML) in climate change studies has become an important area of research.

The comprehensive search and review of published literature on the application of ML in CC studies shows that over 2706 documents have been indexed in the Elsevier Scopus database. With over 213 reviews and conference review publications on the topic, there is an urgent need to systematically analyze and present a holistic overview of the current status of the research landscape on the application of ML in CC (MLCC) research (. Bibliometric analysis is considered an important approach for exploring and analysing the scientific literature to highlight the current growth and future developments of any field of research [13,14]. To the best of the author's knowledge, there is currently no publication in the Scopus database on the bibliometric analysis of MLCC research. Therefore, this paper presents and examines the research/publications landscape on machine learning (ML) applications in climate change (CC)

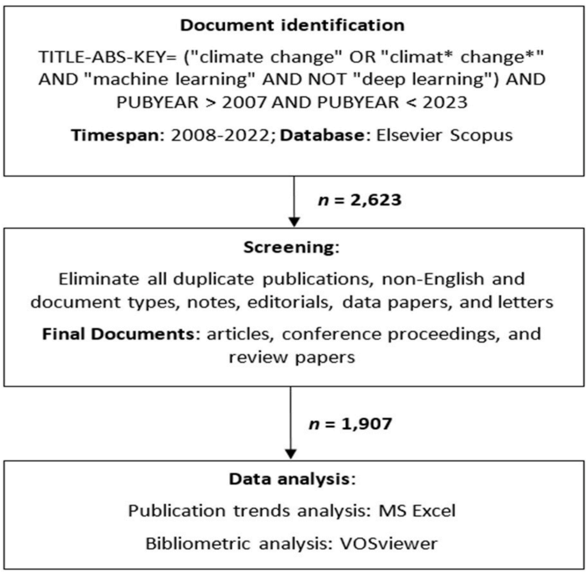

Fig. 1. PRISMA methodology for published documents data recovery, screening, and analysis.

research based on published documents data between 2008 and 2022. It is envisaged that the selected timeframe will provide current researchers and future stakeholders with critical insights into the current status and future directions of MLCC research.

2. Methodology

This paper aims to examine the current research landscape on the applications of machine learning algorithms in tackling the global challenge of climate change. To this end, we determined that we needed to employ a method that would provide greater accuracy in determining the sample database. Hence for this reason, we followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) principles proposed by Ref. [15]. The PRISMA approach, was adopted to identify, screen, and analyze published documents (or publications) for a bibliometric review (Fig. 1).

To achieve these abovementioned objectives, the methodology of the study, involved analysis of the publication trends using recovered data on the articles that have been published on the subject from the Elsevier Scopus database and bibliometric analysis techniques were adopted to identify, screen, and analyze all the published documents on the topic published and indexed in the Elsevier Scopus database. Consequently, the Elsevier Scopus database was selected to identify related publications on the applications of machine learning in climate change research (hereafter shorted as MLCC research) published and indexed in the database over the 30 years selected for the study. An appropriate search string was subsequently developed and deployed in Scopus to identify related documents on the topic in the literature. Fig. 1 shows the flowchart of the PRISMA analysis and data recovery approach used in this study.

On the January 11, 2023, the following search string TITLE-ABS-KEY criteria ("climate change" OR "climat* change*" AND "machine learning" AND NOT "deep learning") AND PUBYEAR >2007 AND PUBYEAR <2023 was executed in Scopus. The search returned 2623 document results comprising various duplicate entries, unrelated documents as well as non-English, unconventional, or non-peer reviews document types. Consequently, screening was performed to eliminate all the duplicate publications, as well as the document types such as notes, editorials, data papers, and letters. The total number of resulting publications was 1907 documents comprising articles, conference proceedings, and review papers published exclusively in the English language between 2008 and 2022. The publication data was subsequently exported to Microsoft Excel (version 2016) for publication trends (PT) analysis, whereas the CSV version was exported to VOSviewer (version 1.16.18) for bibliometric analysis (BA).

The PT analysis was performed to examine the growth pattern of the publications along with the top authors/researchers, affiliations, countries, and funding bodies actively involved in the research on the topic. On the other hand, the BA was performed to examine the co-authorship, keyword co-occurrences, and citation networks on the topic using VOSviewer software. The software was used to generate visualisation maps of the networks to determine the impact of collaborations, hotspots, and research impact of the topic in the literature. The findings of the PT and BA analyses are critical to examining the Research/Publications Landscape on Machine Learning Applications in Climate Change Research over the time frame of 2008–2022 examined in this study. Section 3 of the paper presents the results and discussions on the PT-BA analysis of the MLCC research.

3. Results & discussion

3.1. Published documents analysis

Fig. 2 shows the growth trajectory of publications on MLCC research over the period examined in this study. As can be seen, a total of 1907 documents comprising 1577 (82.5%) articles, and 335 (17.5%) conference papers have been published on the topic between

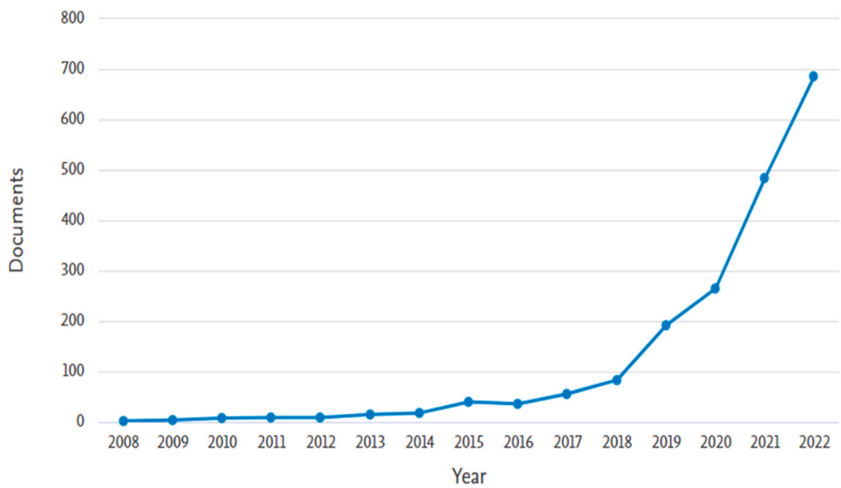

Fig. 2. Growth trajectory of published documents on MLCC research (2008–2022).

2008 and 2022. The publication trends analysis shows that the number of publications on the topic increased significantly from 2 to 691, which represents an enormous 34,450% in publications on the topic in 15 years. However, in the first ten years from 2008 to 2017, the publications output was low i.e., <60 or 19.7 per year compared to 343 per year between 2018 and 2022. The information in Fig. 2 is relevant because it illustrates that there is a proportionate increase in researchers' interest in the application of machine learning in addressing climate change and its related environmental issues such as global warming.

According to numerous analyses, climate change is one of the greatest threats to human existence owing to its potential impacts on humanity as well as the social, environmental, and economic systems around the globe. According to various environmental/climate reports, the global average temperature (GAT) has risen by about 0.85 °C (1.53 °F) between 1880 and 2020 [16,17]. The data shows that the planet GAT has increased by 0.08 °C (or 0.14 °F) every ten years since 1880, although the rate of warming has more than doubled per decade to 0.18 °C (0.32 °F) since 1981 [18]. Due to the changes in GAT, scientists predict that climate change could result in net damages with significant costs to humanity and the environment [17]. According to some analysts, some regions of the world are already experiencing higher rainfalls, more floods, mudslides, rising ocean levels, loss of habitat, as well as severe heat waves [16].

As a result, numerous analysts, policymakers, and scientists around the globe have prioritized the search for strategies, tools, and systems to increase the understanding of the global challenges immediately and potentially posed by climate change and global warming. The multidimensional nature of climate change has prompted multidisciplinary studies spanning different subject areas. Table 1 shows the top 10 subject areas in which MLCC research studies are categorized in the Scopus database. As can be seen, MLCC research is indexed in numerous categories namely science, technology, engineering, and mathematics as well as the arts, humanities, and social sciences. The findings indicate MLCC is a broad, multifaceted, and multidisciplinary area of research which confirms the earlier submission of its social, economic, and environmental impact. Further analysis shows that the two most prominent subject areas in MLCC research are Environmental Science and Earth & Planetary Sciences, which account for 779 and 566 published documents or 21.60% and 15.69% of TP, respectively.

The findings suggest major studies on MLCC research have been focused on the impacts of climate change on agricultural production [19], weather conditions [20], and disaster prediction and preparedness [21], among others. The study by Crane-Droesch [19], examined the application of ML techniques in predicting the impact of CC on methods for corn crop yields in the United States. The impact assessment of crop yield was examined using a semi-parametric, and cross-sectional heterogeneous deep neural network approach. The results showed that CC has significant adverse effects on the yield of corn production, which could have long-term impacts on not only the environment but the socio-economic well-being of the farmers, regions, and global food chain.

On the other hand, O'Gorman and Dwyer [20], employed an ML-based decision trees (random forest) algorithm to investigate the effect of CC on the convection of moisture which can significantly affect climate modelling and weather predictions. The results showed that ML successfully modelled the interaction between convection and largescale environment which provides an avenue to simulate the impacts of CC on weather conditions. Huntingford et al. [21] demonstrated the use of ML in identifying teleconnection, simply complex feedback as well as diagnosing, analysing, or visualise earth system models used to better predict and understand CC impacts For instance, ML may aid teleconnection identification, where complex feedbacks make characterisation difficult from direct equation analysis or visualisation of measurements and Earth System Model (ESM) diagnostics. Other notable studies that resulted in breakthroughs in the analysis of CC and its impacts on biodiversity [22,23], floods [24,25], rainfall [26,27], as well as buildings energy [28,29], and physical infrastructures [30,31], among others. The review of literature has highlighted the importance of ML in CC studies and the need to better understand its impact on humanity and the environment. Section II presents an overview of the most cited publications on MLCC research over the years.

3.2. *Highly cited publications*

Table 2 presents the top 10 most highly cited publications on MLCC research from 2008 to 2022 based on results from the Scopus database. The most cited publications on MLCC have garnered a total of 5736 citations, which account for 21.17% of the total citations of all publications on the topic. Hence, it can be reasonably surmised that the publications in Table 2 are the benchmark studies on MLCC between 2008 and 2022 based on citation criteria. As can be seen, the most cited publication on the topic is Hengl et al. [32], which has been cited 1661 times in the literature. The study demonstrated that ML-based tools (such as SoilGrids 250 m) could be used

Table 1
Subject categories of publications on MLCC research (2008–2022).

Subject Area	Total publications (TP)	Percentage of total publications (%TP)
Environmental Science	779	21.60
Earth & Planetary Sciences	566	15.69
Computer Science	438	12.14
Agricultural & Biological Sciences	409	11.34
Engineering	335	9.29
Social Sciences	228	6.32
Energy	163	4.52
Mathematics	133	3.69
Physics and Astronomy	120	3.33
Biochemistry, Genetics, & Molecular Biology	100	2.77

to obtain spatial information on soil water parameters, particularly in regions adversely impacted by climate change. Such findings provide critical information for modelling soil properties (such as soil organic carbon) which play an important role in the productivity of agriculture [32].

The second most cited publication is by Jung et al. [33] which has gained 1461 citations to date. In the study, the authors showed that the impact of climate change on global land evapotranspiration could be examined using ML algorithms combined with a worldwide monitoring network, and climatological and remote-sensing techniques. The results showed that the yearly average rate of global evapotranspiration rose by 7.1 ± 1.0 mm per year between 1982 and 1997 although this trend ceased in 2008. With ML the authors were able to access the status of soil moisture in the hydrological cycle over extended periods which could be crucial in predicting CC impacts, particularly in vulnerable regions in the coming years. Other cited publications have examined CC impacts on various aspects of the environment from soil carbon [34], soil microorganisms [35], groundwater pollution [36,37], agricultural produce and yields [38,39], and soil properties [40].

The high citation rates of the publications in Table 2 reflect not only the research impact of the studies but also the socio-economic, and environmental importance of climate change studies. As observed in the publication trends analysis, MLCC research has experienced significant growth over the years, which has also resulted in high citations (27, 089) in total over the last 15 years. High citations can also be associated with extensive collaborations or co-authorships between researchers with their peers based on their affiliations or others in various networks around the world [42,43]. Fig. 3 shows the network visualisation map for the co-authored publications on MLCC research deduced based on a minimum of 5 citations per publication using VOSviewer.

The results indicate that 35 (i.e., 4.19%) of the 835 published documents with 5 or more citations are due to collaborations between authors on MLCC research. This indicates that the high rates of citations on the topic are not due to collaborations, as also evident in the thin lines connecting the nodes of the author citations. Therefore, the citation rates may be due to other factors such as the research impact, source titles or reputation of the authors, affiliations, or countries where the studies have been carried out. The influence of the outlined factors will be examined in sections III to VII of the paper.

3.3. Source journal titles

Fig. 4 shows the most commonly used source titles for publications on MLCC research between 2008 and 2022 based on data from Scopus. As can be seen, the top source titles on the topic are Remote Sensing, Science of the Total Environment (TOTEN), Sustainability (Switzerland), Journal of Hydrology, and Water (Switzerland) as shown in Fig. 4.

The top 5 source titles have published 312 documents or 16.36% of the total publications on the topic over the years. The top journal on the topic is *Remote Sensing* which has published 121 documents, which account for 6.35% of TP. It is described as a bimonthly open-access journal that publishes manuscripts on the application of remote sensing and photogrammetric technologies. Its high output could be ascribed to its high impact factor and open access feature, which according to various studies in the literature has a strong correlation with productivity and citations [44,45]. This observation may somewhat explain the presence of other MDPI (Multidisciplinary Digital Publishing Institute) journals such as *Sustainability* (49 published documents or 2.57% of TP) and *Water* (32 published documents or 1.68% of TP) in the top 5 journals on MLCC research. Therefore, it can be reasonably surmised that the productivity of the top journals on the topic is largely due to the reputation of the source titles or journals, as well as the open-access nature of the journals.

Table 2
Top 10 most highly cited publications on MLCC research (2008–2022).

Authors/References	Publication Titles	Journal titles	Cited by
Hengl et al. [32]	SoilGrids250 m: Global gridded soil information based on machine learning	PLoS ONE	1661
Jung et al. [33]	Recent decline in the global land evapotranspiration trend due to limited moisture supply	Nature	1461
Aminikhanghahi and Cook [41]	A survey of methods for time series change point detection	Knowledge and Information Systems	500
Sanderman et al. [34]	Soil carbon debt of 12,000 years of human land use	Proceedings of the National Academy of Sciences of the United States of America	442
van den Hoogen et al. [35]	Soil nematode abundance and functional group composition at a global scale	Nature	391
Podgorski and Berg [36]	Global threat of arsenic in groundwater	Science	372
Bunn et al. [38]	A bitter cup: climate change profile of global production of Arabica and Robusta coffee	Climatic Change	244
Forkuor et al. [40]	High-resolution mapping of soil properties using Remote Sensing variables in south-western Burkina Faso: A comparison of machine learning and multiple linear regression models	PLoS ONE	233
Rodriguez-Galiano et al. [37]	Predictive modelling of groundwater nitrate pollution using Random Forest and multisource variables related to intrinsic and specific vulnerability: A case study in an agricultural setting (Southern Spain)	Science of the Total Environment	232
Cai et al. [39]	Integrating satellite and climate data to predict wheat yield in Australia using machine learning approaches	Agricultural and Forest Meteorology	200

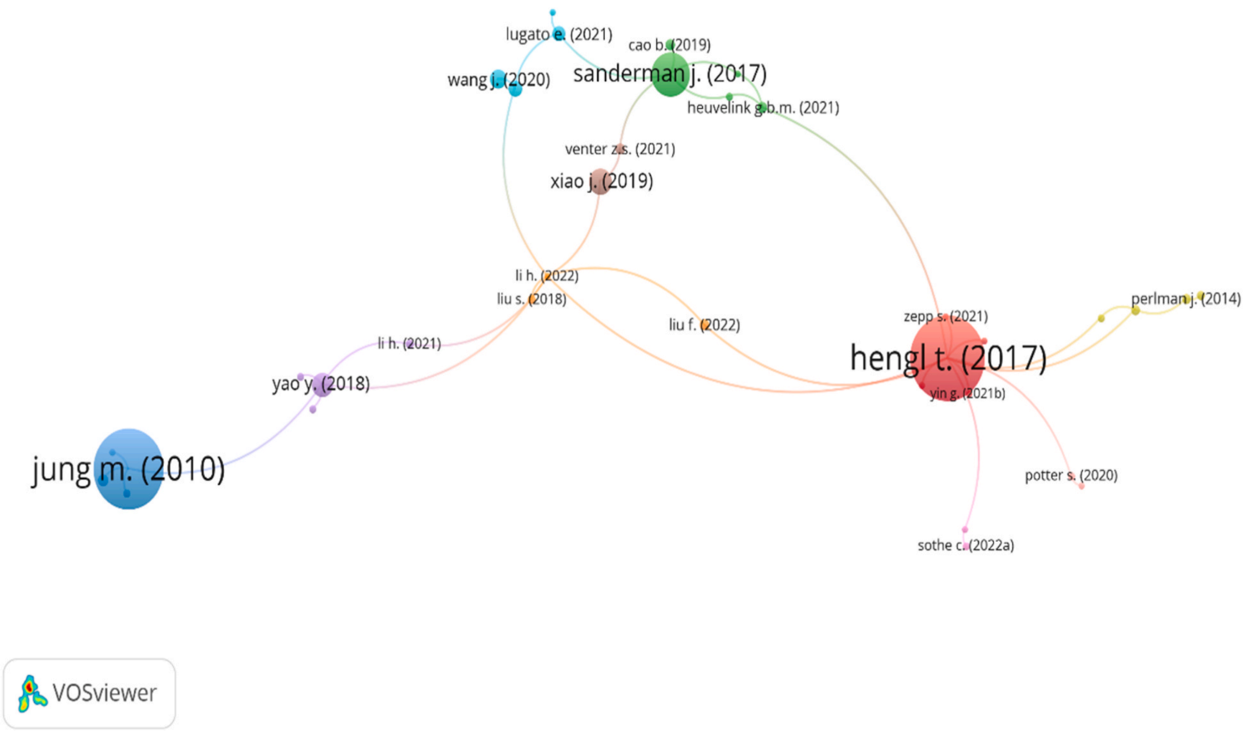

Fig. 3. Network visualisation map for co-authored publications on MLCC research (2008–2022).

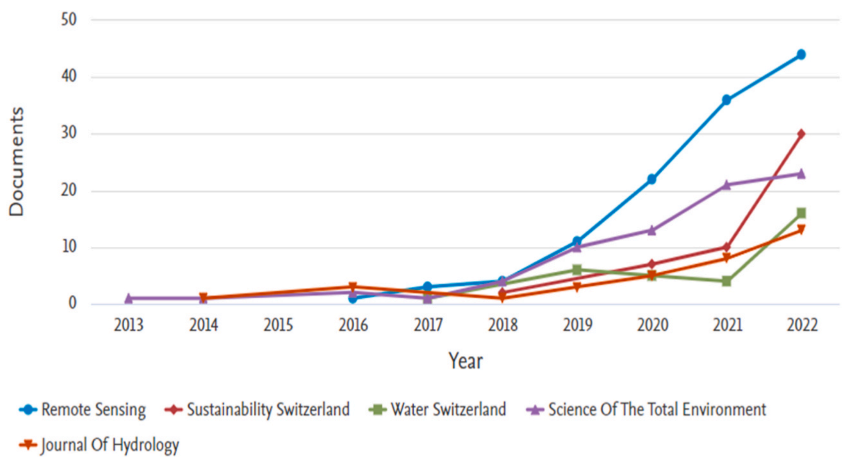

Fig. 4. Top source titles for publications on MLCC research (2008–2022).

The influence of journal reputations on the citations and productivity of journals can be further examined through the citation analysis feature of VOSviewer. Fig. 5 shows the network visualisation map for journal citations on MLCC research between 2008 and 2022 deduced based on the minimum of 5 documents and 50 citations per source title.

The findings showed that 47 source titles out of the possible 687 that have published articles on the topic satisfied the set criteria. Further analysis shows that 42 (89.36%) of the 47 source titles have one or more co-citations. The journal with the highest number of citations is PLOS One (2463), followed by TOTEN (1,633), and the last is *Remote Sensing* (1,201). The highest total link strength (TLS) of any source title was observed for *Remote Sensing* (39), which has strong citation links with others such as TOTEN (25), and Agricultural and Forest Meteorology (24). The findings indicate that the most prominent journal on MLCC research is *Remote Sensing* based on its high output/productivity, citations, and TLS. The outlined factors along with its high impact factor (IF = 5.349), open access and citation potential account for its selection by top authors in the field for publication of manuscripts on the topic. Sections IV-VI will identify and highlight the top stakeholders on the topic in the literature.

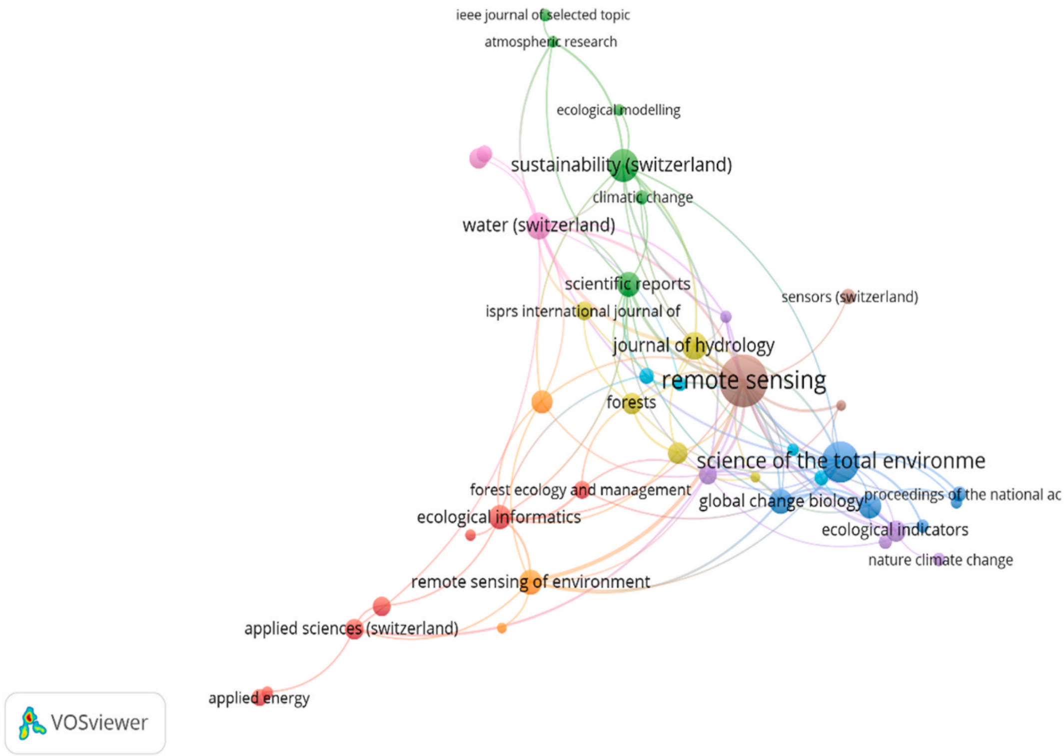

Fig. 5. Network visualisation map for journal citations on MLCC research (2008–2022).

3.4. Top authors/researchers

Fig. 6 shows the top 5 most prolific authors/researchers that have been involved in MLCC research from 2008 to 2022 based on data in Scopus. As can be seen, the top 5 authors have published 6 or more publications or a total of 40 (or 2.10% of TP) during the timeframe examined in the study. Further analysis shows that the top 5 most prolific authors and their affiliating country are as follows; Shamsuddin Shahid (Malaysia), Falk H. Huettmann (United States), Jungho Im (South Korea), Ali Jamali (Canada), and lastly, Quoc B. Pham (Poland).

The most prolific author on the MLCC is Shamsuddin Shahid who is based at the *Universiti Teknologi* Malaysia with 14 publications (or 0.73% of TP) on MLCC, which have been cited a total of 295 times gaining an h-index of 8. The most cited/prominent publication by the author is "Prediction of droughts over Pakistan using machine learning algorithms" published in the *Advances in Water Resources* with 94 citations to date [12]. The study employed three advanced ML methods namely; Support Vector Machine (SVM), Artificial Neural Network (ANN) and k-Nearest Neighbour (KNN) to develop models for drought prediction in Pakistan. In another study cited 52

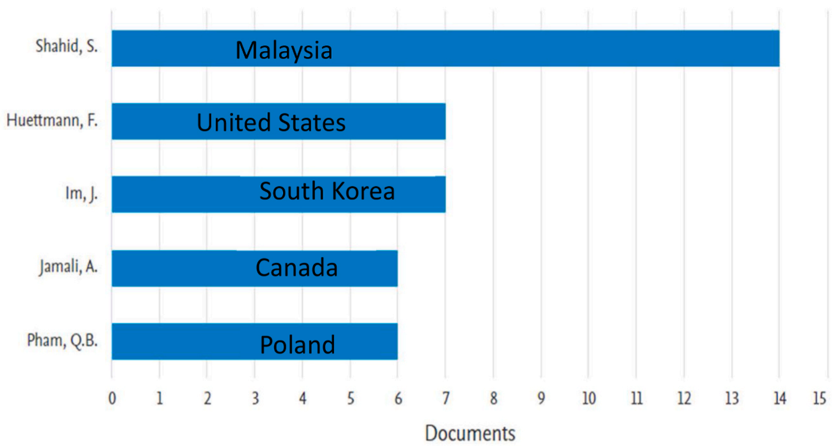

Fig. 6. Top 5 authors and country of origin on MLCC research (2008–2022).

times, Shahid and co-workers [46], proposed and examined a Multiple Criteria Decision Making (MCDM-based) structure for estimating Spatiotemporal rainfall changes in Nigeria using general circulation models. The author's studies have generally been focused on utilising ML techniques to predict water-based issues [47,48] such as droughts [49], rainfall (precipitation) [50,51], and marine life [52], along with weather and climatic conditions [53,54] in the tropical regions of the world.

Falk H. Huettmann (the University of Alaska Fairbanks, United States) and Jungho Im (Ulsan National Institute of Science and Technology, South Korea) are the second most prolific authors with 7 publications each on the topic. The works of Falk H. Huettmann (cited 145 times, *h*-index = 6) have been largely focused on using ML techniques to investigate the impacts of climate change on plant and animal species with the aim of sustainable conservation of their biodiversity. The most prominent/cited work of Falk H. Huettmann is "Rapid multi-nation distribution assessment of a charismatic conservation species using open access ensemble model GIS predictions: Red panda (*Ailurus fulgens*) in the Hindu-Kush Himalaya region" published in the journal "Biological Conservation" with 55 citations to date. In the study, the authors used data mining and ML techniques to identify new populations and restore extinct or threatened species of the red panda (*Ailurus fulgens*) in the Hindu-Kush Himalaya region. The study showed that the use of GIS and ML-based algorithms provide practical resources to understand the bio-geographical evolution of the species, which could help in the effective conservation and management of globally threatened species. In general, the author's studies have largely focused on the use of ML to examine the effects of climate change on mammal distributions, population decline, forest classification, and species conservation.

On the other hand, Jungho Im has dedicated his research to applying ML to climate change issues such as droughts, greenhouse gas emissions, as well as, sea ice detection, which has cumulatively garnered 314 citations with an *h*-index = 6. The most notable study by the author is "Drought assessment and monitoring through the blending of multi-sensor indices using machine learning approaches for different climate regions" [55], which has been cited 186 times. In the study, the authors adopted remote sensing and ML tools to examine the meteorological and agricultural impacts of drought during the growing season in diverse climatic regions of the United States from 2000 to 2012. The results showed that the RS and ML tools successfully generated drought distribution maps, which could be utilised in the future to assess and monitor droughts in the future [55]. In general, the review of literature on the top authors shows that MLCC research has a high research impact, which points to even higher output, citations, and collaborations.

Collaborations play a crucial role in the growth and development of any given area of research. It is considered an impact

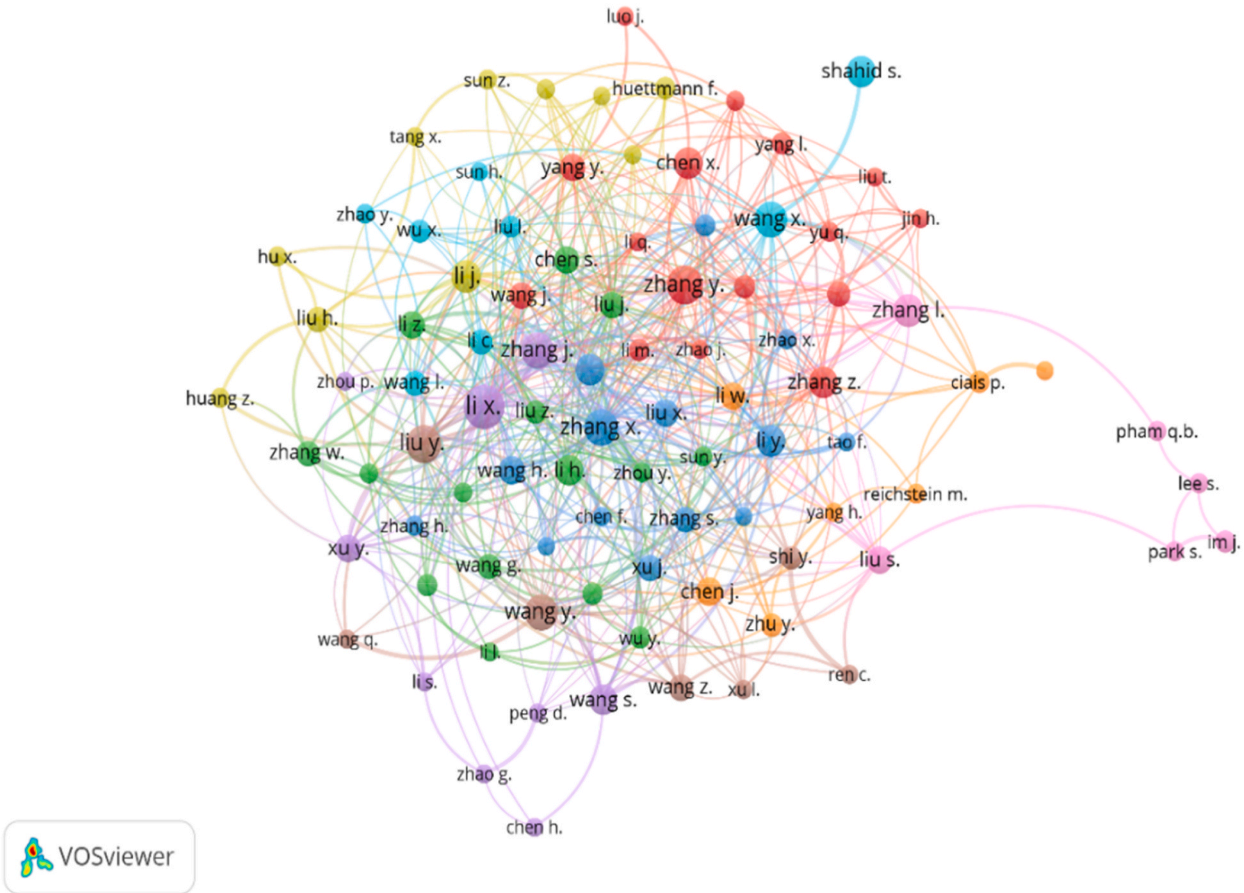

Fig. 7. Network visualisation map of co-authorship among MLCC researchers (2008–2022).

measurement of the research impact and productivity of the researchers involved in any field. In this study, the extent of collaboration between the top authors was examined using the co-authorship analysis feature of VOSviewer software. Fig. 7 shows the network visualisation map of the level of co-authorship among MLCC researchers based on Scopus data. The map was generated based on the set criteria of 5 documents and 5 citations per author, which resulted in 99 authors who fulfilled the criteria. Further analysis shows that 92/99 (i.e., 92.93%) have co-authored one or more publications on MLCC research, which suggests that collaboration among the top authors is significantly high. The findings may also explain the high rate of citations and by extension the research impact of the topic.

The author with the most co-authored documents is Li X (28), followed by Zhang Y (22), and lastly Liu Y (21). Similarly, Li X (27) is the most prominent researcher on MLCC research, followed by Zhang X and Liu Y who both have TLS of 16 each. Based at the Zhejiang Agriculture and Forestry University in Hangzhou (China), the author Li X (Xuejian Li) has the highest number of co-authored documents and TLS. The prolific nature of the author and co-workers could be due to either support or other forms of research-based resources from their institutions, countries or funding agencies as will be examined in Sections V – VII.

4. Most research active affiliations

Fig. 8 shows the top 5 affiliations/institutions actively involved in MLCC research around the globe. Typically, host institutions provide authors, scientists, and researchers with resources in various forms such as infrastructure, finance, and other skilled personnel to successfully research various topics of interest. In this study, the top institutions researching MLCC topics were examined based on Scopus data. As can be seen, the top institutions are the Chinese Academy of Sciences, the University of Chinese Academy of Sciences, the Ministry of Education China, *Centre National de la Recherche Scientifique* (CNRS), and the Institute of Geographical Sciences and Natural Resources Research Chinese Academy of Sciences. The top five institutions account for 290 publications or 15.21% of TP, which indicates these are the most prolific institutions engaged in research on the topic worldwide. As observed, the top five affiliations are dominated by China-based institutions with the top position occupied by the Chinese Academy of Sciences with 121 publications (or 6.35% of TP), which have been cited 2298 times with an *h*-index of 25. The most notable works from the institution include Sun et al. [56], van den Hoogen et al. [35], and Xiao et al. [57], which examined the use of ML and RS tools to investigate CC impacts on water, soil microbe diversity, and carbon cycles.

However, it is important to state that the studies are largely based on collaborations between researchers at CAS and others worldwide. This observation indicates collaborations and co-authorships have been crucial to the growth and development of MLCC research studies, as depicted in Fig. 9.

The results indicate that 260 institutions have published two or more publications that have in turn been cited at least twice over the time frame examined in the study. However, the analysis of the level of collaboration between these institutions shows that only 65 (or ~25%) have co-authored publications. However, the most extensive collaboration network of any institution is the University of Chinese Academy of Sciences (UCAS) which has co-authored 30 publications with other institutions and gained a TLS of 19 compared to the Institute of Research and Development Duy Tan University (Vietnam), and the State Key Laboratory of Desert and Oasis Ecology, Chinese Academy of Sciences. Based on the findings, UCAS is the most prominent institution of MLCC research in the world.

5. Top researching countries

Fig. 10 shows the top 5 countries actively involved in MLCC research around the world based on Scopus data from 2008 to 2022. As observed, the top five nations have each produced over 1350 more publications (or 270.6 on average), which account for over 70.95% of TP on the topic. This represents an enormous scientific and scholarly contribution to the field of MLCC research.

As seen in Fig. 10, the most prolific country on MLCC is the United States 506 publications or 26.53% of TP on the topic. The high

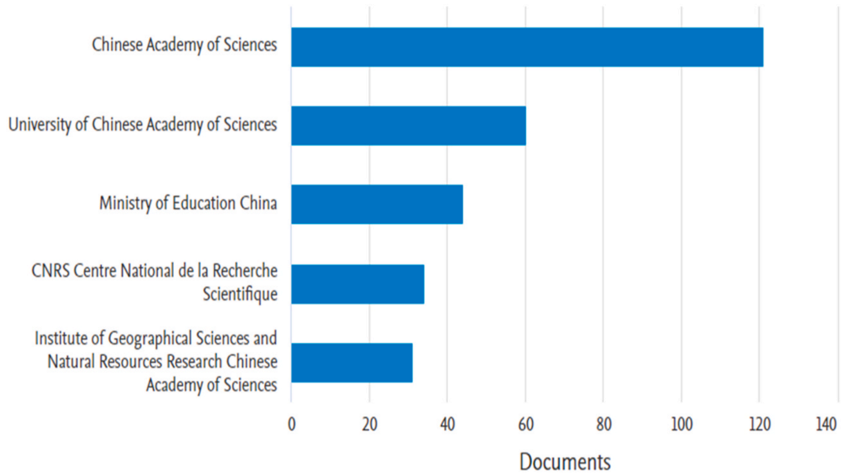

Fig. 8. Top 5 affiliations/institutions on MLCC research (2008–2022).

Fig. 9. Network visualisation map of collaborations MLCC research institutions (2008–2022).

productivity of the US is due to the works of Falk H. Huettmann of the University of Alaska Fairbanks, (United States) as earlier surmised as well as others like Gregory P. Asner (5 publications, Arizona State University), Elizabeth A. Barnes (4 publications, Colorado State University), and Steven P. Brumby (4 publications, National Geographic Society, Washington, D.C.). The lead of US is followed by China and India with 377 and 174, respectively.

The presence of the United States, China, and India in the top 5 nations on MLCC is largely connected to their status as highly industrialised nations that emit significant quantities of carbon dioxide and other greenhouse gases responsible for global warming and climate change. As a result, research in the three nations (who are also a signatory to the 2015 Paris Agreement in France) has focused on understanding the impacts of CC using various strategies and technologies including but not limited to RS and ML techniques. Due to the global impact of GW and CC, such research has also required and involved collaborations between the top three and other nations resulting, which has resulted in high numbers of publications, citations, and other forms of research output over the years. Fig. 11 shows the network visualisation map for the degree of co-authorship among the countries actively engaged in MLCC research over the 15 years examined in the study.

The findings indicate that 137 countries have published five or more publications which in turn have received at least five citations between 2008 and 2022. The United States has the most co-authored publications at 504 (cited 11,970 times, TLS = 272), which is closely followed by China (376 with 6637 citations, TLS = 168) and India (174). Based on the findings, the United States is not only the most prolific but also the most prominent stakeholder in the research landscape on the application of machine learning in climate change studies worldwide. However, China and India are not far off with collaborations between the three countries expected to increase over the years with increasing global calls for the duo to cut down on GHG emissions particularly coal-fired electricity

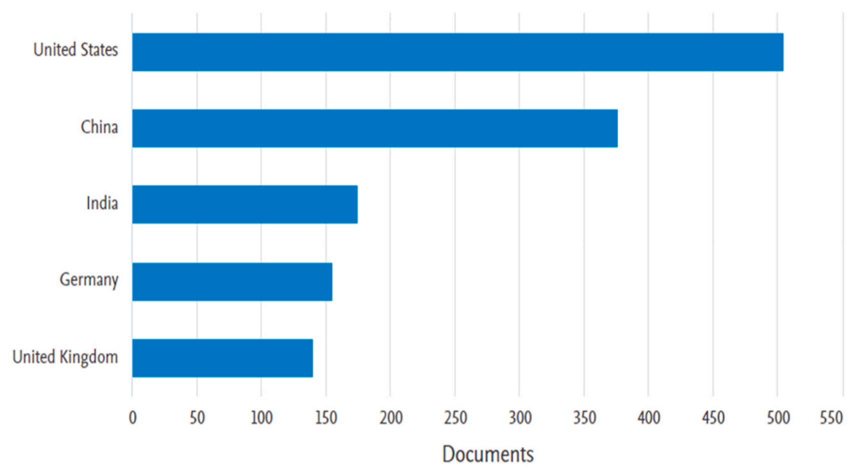

Fig. 10. Top 5 countries actively involved in MLCC research (2008–2022).

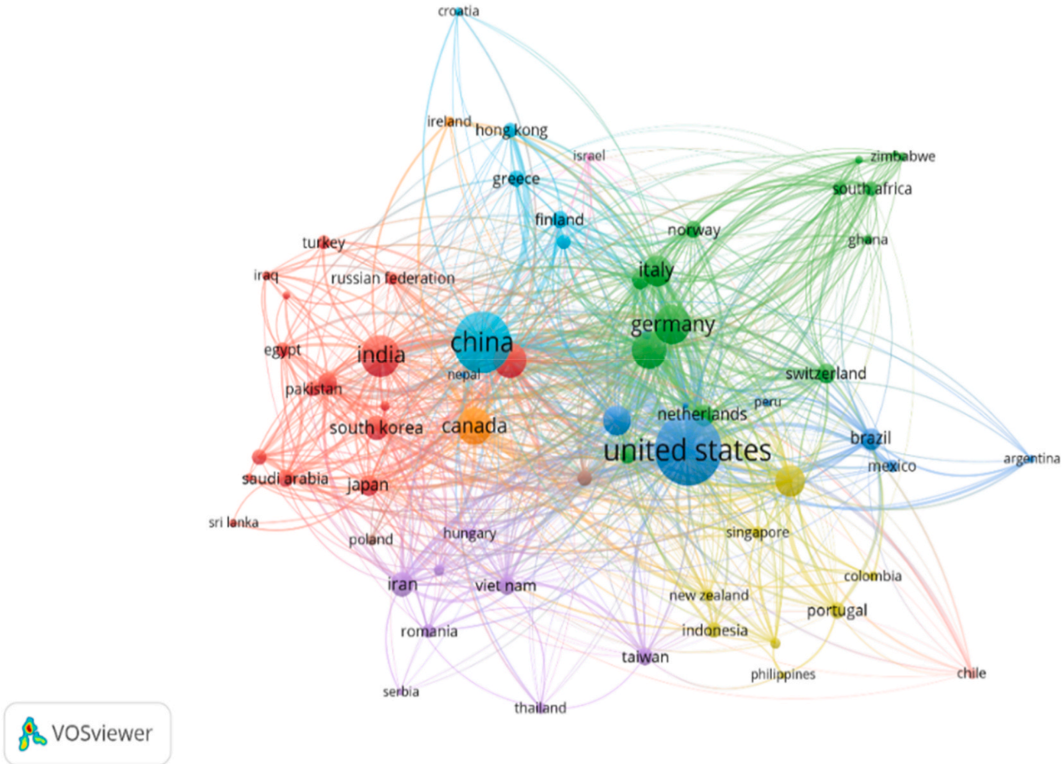

Fig. 11. Network visualisation map for country co-authorship on MLCC research (2008–2022).

production. Hence, it is expected that increased funding and investments in the top 3 countries will increase and enhance the research into ML and other technologies such as artificial intelligence, internet of things (IoT), among others. It is envisaged that this will go a long way in improving the understanding of GW and CC as well as better predict, mitigate, or curb their current and future impacts on mankind and the environment.

5.1. Top funding organisations

The accessibility of funding is critical to the growth and development of any field of study or research endeavour [58,59]. Funding avails researchers of the platform for providing much-needed resources such as infrastructure, and equipment, along with monies for salaries, and other forms of remuneration needed for successfully carrying out research [60–62]. In addition, the provision of funding is also considered an important determinant of research and citation impact as well as the nature, motivation, and quality of research

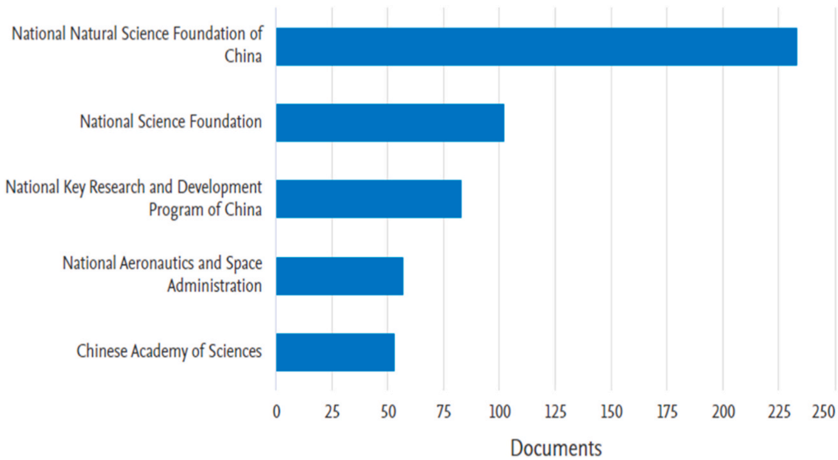

Fig. 12. Top 5 funding organisations for MLCC research (2008–2022).

[63–65]. Access to research funding also provides an avenue to foster and maintain diversity in academia [66], as well as fruitful collaborations between various research groups [67,68]. Therefore, the nature and extent of research funding on the growth and development of MLCC research were examined. Fig. 12 shows the top 5 funding organisations actively involved in MLCC research based on Scopus data from 2008 to 2022.

The top funder of MLCC research is the National Natural Science Foundation of China (NSFC) as shown in Fig. 12. As can be seen, the NSFC has funded a total of 234 research projects over the last 15 years which have gained 2812 citations with an *h*-index of 27. The most notable publications funded by the agency are the works of Fulu Tao (5 publications), Yaning Chen (4), and Xiangang Hu (4) who are based in institutions such as the Chinese Academy of Sciences, and Nankai University among others in China. The studies funded by the agency have been largely focused on the use of ML to examine CC impacts on climatic/environmental conditions [69,70], aboveground biomass/forest cover [71,72], soil/topographic properties [73], as well as agricultural crop yields [74]. In the United States, the most notable funder is the National Science Foundation (NSF) which has funded a total of 103 publications (4443 citations, *h*-index = 25) on the topic over the years. Notably, the NSF has funded the studies Van Den Hoogen et al. [75], Aminikhanghahi and Cook [41], and Cai et al. [76], which have been focused on applying ML to investigating CC impacts on crop/agricultural yields, soil, and microbe diversity among others.

5.2. Keywords Co-occurrence analysis

Fig. 13 and 14 show the network visualisation and overlay visualisation maps of keywords co-occurrences in MLCC research. The analysis of the co-occurrence of keywords in any given area of research provides critical insights into the formation of clusters or hotspots or themes in any area of research [83,84], otherwise termed knowledge mapping [85,86]. In this study, the analysis of the co-occurrence of keywords was examined using VOSviewer software. Consequently, the network visualisation map of the keywords on MLCC research was mapped as shown in Fig. 13. The map shows that out of the 13,550 keywords deduced from MLCC research, a total of 69 have at least 50 citations in Scopus which can be grouped into 4 clusters comprising 5 to 26 words. The highest occurring keywords are climate change (1,479), machine learning (1,346), and decision trees (341) with TLS 7,374, 6,615, and 2,609, respectively. Other notable keywords include learning systems, articles, forecasting, remote sensing, and climate models among others. The cluster analysis of the keywords co-occurrence showed that 4 major clusters exist in the MLCC research in the literature [87]. The largest (red) cluster which comprises 26 keywords such as artificial intelligence, artificial neural networks, climate change, and machine learning describes the various computation models/tools, methods/strategies, and technological systems currently utilised for examining/understanding the impacts of climate change. Hence, this can be described as the core/primary cluster of MLCC research. Other keywords such as crops, floods, rain, and weather forecasts indicate the various impacts of CC that are currently focal areas for researchers involved in MLCC research worldwide.

The second (green) cluster comprises 23 keywords such as agriculture, climate, carbon sequestration, ecosystems, humans, land use, environmental monitoring, China, and the United States among others describe the various applications, sectors, and regions in which ML is applied to understand the impacts of CC. One of the largest applications of ML is in monitoring the impacts of CC on the environment through controlled studies and spatiotemporal analysis. Such studies examined the impact of CC on the various forms of carbon present in soils, forests, and other ecosystems along with climatic conditions such as temperature and precipitation. Hence, this cluster can be termed the intermediate cluster which links tools to applications of MLCC research. Cluster 3 (blue) consists of 15 keywords such as mapping, remote sensing, satellite data, satellite, imagery, and Landsat. These combinations of keywords describe the use of remote sensing as an individual tool or combined with machine learning algorithms to examine the impact of CC on various environmental ecosystems such as biodiversity, vegetation, forestry, or forest cover. Based on the above, this cluster could be termed the subordinate or referral cluster which adds to the body of knowledge on MLCC. Lastly, cluster 4 (lime green/yellow) includes the keywords carbon dioxide (CO_2), greenhouse gases, global warming, machine learning models, and sustainable development. Hence, this cluster describes the potential of applying ML in mapping global warming (in addition to climate change), which is caused by the emission of CO_2 and other GHGs. This cluster also shows that the application of ML in CC studies is critical to sustainable development, which is a key component of the United Nations Sustainable Development Goals initiative. Overall, the cluster analysis showed that MLCC is a broad, impactful, and multidisciplinary area of research that is poised to not only remain relevant but continue to grow geometrically in terms of publications output, citations, and scientific influence.

6. Conclusions

The paper presented a comprehensive analysis of the research/publications landscape on the application of Machine Learning in Climate Change Research based on data recovered from the Scopus database from 2008 to 2022. The publication trends revealed 1907 published documents exist in the selected database, whereas the topic has experienced significant growth (>34,450%) over the last 15 years. The high growth rate observed can be attributed to the socio-economic and environmental importance of the topic, as well as its interdisciplinary nature as deduced by the subject area analysis. The study showed that the research focus has been largely on understanding, as well as limiting the impact of climate change in the areas of water management, agriculture, meteorology, disaster prediction as well as other socio-economic and environmental sectors. Bibliometric analysis revealed that the high productivity on the topic is majorly due to collaborations between the top authors, affiliations and countries involved in MLCC research as deduced from the co-authorship analyses. Other factors include research funding from major funders based in China and the United States although funding for research in India was somewhat limited. The study also showed that the concentration of funding between the US and China created research hotspots/themes which were analysed through keywords co-occurrence analysis. The findings revealed 4 key

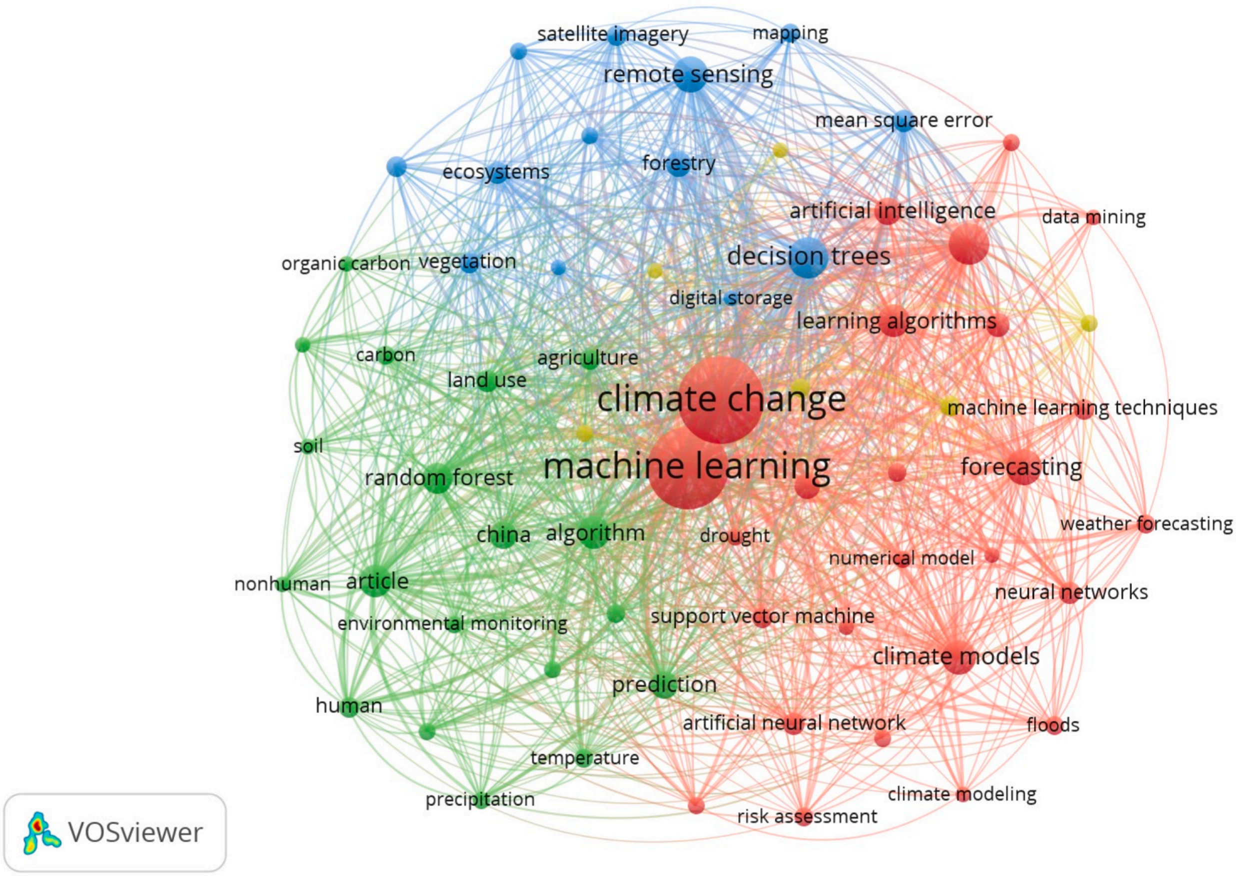

Fig. 13. Network visualisation map of keywords co-occurrences on MLCC research (2008–2022).

research hotspots that describe the tools/systems of ML used to examine CC impacts, potential sectors or areas of application, additional tools such as remote sensing, and finally ML tools for assessing global warming impacts on sustainable development. Overall, the paper shows that MLCC research has a significant impact and will remain relevant to current and future researchers seeking to apply computation tools in addressing socio-economic and environmental issues worldwide.

Ethical approval

Not Applicable.

Consent to participate

Not Applicable.

Consent to publish

Not Applicable.

Authors contributions

Samuel-Soma M. Ajibade: Conceived and designed the experiments.
Festus Victor Bekun: Performed the experiments, interpreted the data and Corresponding.
Abdelhamid Zaidi: Wrote the paper, analysed and interpreted the data.
Anthonia Oluwatosin Adediran: Contributed data, analysed and interpreted the data.
Mbiatke Anthony Bassey: Wrote the paper, Contributed reagents, materials and analysis tools.

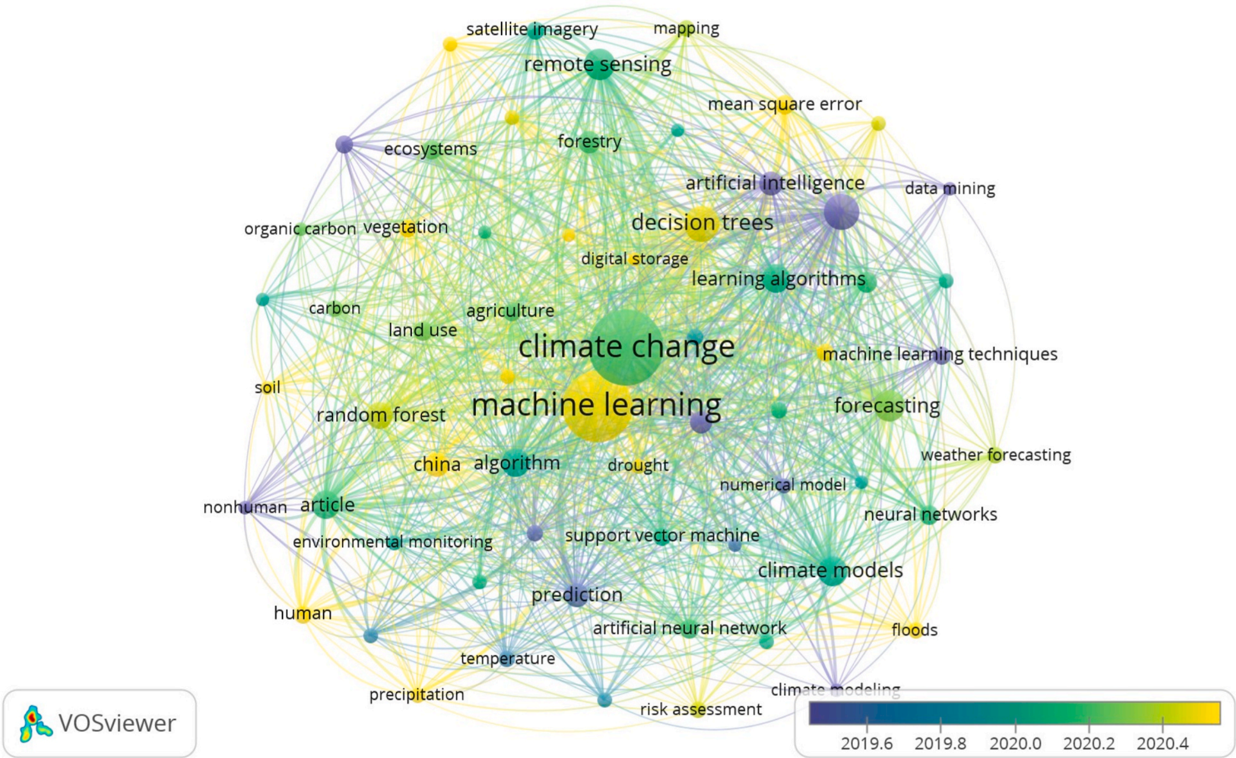

Fig. 14. Overlay visualisation map of keywords co-occurrences on MLCC research (2008–2022).

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Availability of data and materials

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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