Knowledge Domain and Emerging Trends in Vulnerability Assessment in the Context of Climate Change: A Bibliometric Analysis (1991-2017)†

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Abstract: Analysis of the knowledge structure and the evolution of research topics in specific areas has been the focus of information science (IS). Such analysis helps to enrich interested researchers' understanding of the functions, activities and evolving constraints of the knowledge domain. This study aims to investigate the knowledge domain associated with the vulnerability assessment in the context of climate change (VACC) research in this fast-growing field between January 1991 and December 2017. A bibliometric approach, along with CiteSpace software, was used to identify and visualize thematic patterns, landmark articles and emerging trends. The data used for the bibliometric analysis include 6,584 original research articles and reviews published between 1991 and 2017. The results indicate that the number of documents pertaining to VACC presented a general growth trend over the last twenty-seven years. *Climatic Change* was the most productive journal. Among countries, the USA, England and Australia predominated, and the University of Chinese Academy of Sciences and U.S. Geological Survey were the two institutions with the largest amount of VACC research. Existing studies in the field of VACC research have focused primarily on environmental sciences. Importantly, emerging trends in VACC research have shifted away from vulnerability assessments of natural ecosystems based on model simulation methods in the context of climate change toward indicator-based assessments of social ecosystem vulnerability, adaptive capacity and resilience under multidimensional stressors and shocks, which are likely to define the new frontier in the field of VACC research.

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1.0 Introduction

Recent evidence and predictions indicate that climate change is accelerating and will lead to wide-ranging shifts in climate variables, which will in turn result in novel conditions that challenge people's ability to adapt over the coming decades (IPCC 2015) and thereby exacerbate the current vulnerability and inequalities of human ecosystems (Lioubimtseva 2015). In other words, climate change is becoming a truly global social and environmental issue with vast international spillovers. Although adaptation (i.e., adjusting to address ongoing and future climate changes) is increasingly recognized as an urgent and necessary complement to greenhouse gas emissions reductions, the identification of suitable adaptation strategies must start with an assessment of vulnerability (Ford and Smit 2004).

Vulnerability is defined as the degree to which a system is susceptible to the adverse consequences of climate change or is unable to cope with its adverse effects and is dependent on exposure, sensitivity and adaptive capacity (IPCC 2008). Assessing the vulnerability assessments of species, ecosystems and resource-dependent industries or communities to climate change is conducive to exploring structural weaknesses that make a system vulnerable (Tonmoy et al. 2014), identifying effective adaptations and prioritizing management approaches that can minimize impacts and enhance resilience (Füssel 2007).

There has been an evolution in thinking on climate change vulnerability over the last twenty years (Cutter 1996; Adger 1999; Füssel 2007), and a range of approaches to assess vulnerability have been proposed and applied, e.g., Cinner et al. (2013), Singh and Nair (2014) and Pacifici et al. (2015). Given the wide variety of systems (e.g., agricultural, marine and urban) subject to a number of possible climate change and other global stressors, the literature relevant to vulnerability assessments in the context of climate change (VACC) is highly diverse in terms of content and methodology. Accordingly, the number of publications across disciplines (Adger 2006; Joakim et al. 2015) and stemming from a number of different paradigms has grown tremendously (e.g., risk assessment, natural disaster management, urban planning, food security, etc.). As a result, obtaining the main directions, findings, and methodologies from this body of work is an important, but not trivial, task for individual researchers and research teams to remain abreast of key developments in VACC.

However, little attention has been given to the objective and quantitative depiction of the knowledge domain and emerging trends in VACC research thus far. Existing surveys often focus on specific VACC subfields and themes. Tonmoy et al. (2014) discussed the methodological challenges facing indicator-based vulnerability assessment. Giupponi and Biscaro (2015) analyzed the evolution of the vulnerability concept in the research streams of climate change adaptation and disaster risk reduction. McDowell et al. (2016) analyzed systematically published articles related to community-level climate change vulnerability assessments. Räsänen et al. (2016) reviewed human vulnerability under multiple processes. Singh et al. (2017) comprehensively reviewed the knowledge progress of VACC in India. Otto et al. (2017) discussed in-depth social vulnerability to climate change. Jurgilevich (2017) systematically reviewed the dynamics of the individual components in climate risk and vulnerability assessments. Although these fertile surveys offered a focused (and in-depth) perspective, they cover only a fraction of the published articles, did not provide an overall picture of the VACC literature and consisted of limited time windows that do not properly captivate temporal trends in VACC research. In addition, the majority of the literature surveys are qualitative and personalized. This approach tends to lead to over- or under-valuation of the contributions of certain scholars, intentionally or unintentionally.

Scientific advance is essentially a dynamic and cumulative process, as any contribution to a given research field must build upon previous theoretical approaches, research methods and research findings (Shafique 2012). In addition, as an interdisciplinary society, the intellectual progress of a problem solving-oriented knowledge domain is influenced by not only the inner intellectual research tradition/paradigm/research program of this research community itself (Kuhn 1962; Lakatos et al. 1978) but also the developments in neighboring and related knowledge domains (Liu et al. 2015). As an interdisciplinary field, bibliometrics is the application of quantitative tools to the study of scientific communications (Leydesdorff 1995) and has a strong connection with libraries and information science (LIS). In this field, bibliometric maps generated based on co-citation data, may serve information retrieval and show relations between authors, documents and journals (Mazzocchi 2018). Hjørland (2013) studied the relationship between citation analysis and knowledge organization and pointed out that the mapping relationship based on co-citation analysis can be used to represent the social knowledge organization system. Nowadays, bibliometric mapping has become a form of competing or a supplementary approach to knowledge organization (Hjørland 2016), and a dominating method of research on the relationship between research fields, especially in domain-analytic studies on discovering ontological bases and analyzing the evolution of academic communities (Smiraglia 2015). Meireles et al. (2014) identified the cluster of authors and documents by referenced references using domain analysis methods. Their analysis, both concerning inner structure, evolution over time, and their implementation in information spaces is important to better under-

stand how knowledge is produced and can be navigated through (Scharnhorst et al. 2016; Wolfram 2016).

In this present study, we aim to investigate the knowledge domain associated with the VACC research and identify thematic patterns, landmark articles and emerging trends in this fast-growing field between January 1991 and December 2017. As for the analytical tools, this research chooses the information visualization software CiteSpace. CiteSpace is a scientometric software to generate and analyze networks of co-cited references based on bibliographic (Chen 2006). This quantitative research method analyzes the VACC research from a broader and more diverse range of relevant topics than the conventional expert-compiled review approach (Chen et al. 2014). Although this work is not structured as an exhaustive analysis of VACC related literature, it does illustrate the utility of bibliometric techniques for exploring hidden knowledge spaces since it can draw a scientific knowledge map of a particular field by producing and analyzing the co-occurrence network of key words and subject categories (co-word analysis) as well as co-citation networks of authors, documents and journals (co-citation analysis). Such a bibliometric analysis is helped to enrich the contextual understanding of the functions, activities, shared semantics, and evolving constraints of VACC knowledge domains (Smiraglia 2015), meanwhile, is beneficial for the monitoring or scientific developments, investigating its transformation, and predicting future research trends (Zhao et al. 2017; Chen et al. 2012). In particular, this technique offers researchers, particularly research students and "newcomers" to the field, a more comprehensive picture of its overall intellectual development.

2.0 Methodology

2.1 Data collection

The data used for the bibliometric analysis were collected from the Social Science Citation Index (SSCI) and Science Citation Index Expanded (SCI-E) via Web of Science (WoS) (http://webofknowledge.com). Before performing a topic search in WoS, we reviewed previous literature (Singh et al. 2017; Räsänen et al. 2016; Giupponi and Biscaro 2015; Mcdowell et al. 2016) to identify the key terms. This search term included TOPIC: (vulnerab*) AND (climat*) AND (evaluat* OR assess*). A record was considered relevant if any of its terms were found in the title, abstract or keyword fields of the record. The queries resulted in 7,474 records as of December 31, 2017. Filtering out less representative record types, such as proceedings papers and notes (as the major document types are peer-reviewed journal articles with references) enables the intellectual roots of the field under study to be traced. The dataset was reduced to 6,584 original research and review articles. Our selection of the search engines might have excluded some relevant papers, but we consider the sample analyzed here to be sufficiently large to gain a systematic overview of the existing literature. The bibliographic records (e.g., titles, authors, dates, author addresses, subject categories, reference lists) of the 6,584 journal articles were downloaded. Next, we removed duplicates by using the native CiteSpace V (version number 5.1.R8 SE.2017) function. Finally, the sample of 6,584 articles was exported to CiteSpace for further analysis.

2.2 CiteSpace

Although there are many software tools for visualizing knowledge domains such as HistCite, Vosviewer, Bibexcel and Science of Science (Sci2) Tool, few tools are particularly designed to generate a systematic review of a fast-moving and complex field (Hou et al. 2018), especially with function of facilitating the detection and interpretation of emerging trends and transition patterns of non-field expert analysts (Chen et al. 2014). CiteSpace, which is based on co-citation theory and the critical path algorithm and is a freely available software package (http://cluster.ischool.drexel.edu/~cchen/citespace/), developed by Dr. Chaomei Chen, is one of the more balanced and powerful software packages. The application can construct bibliometric networks at different times, including identifying rapidly growing topical areas and citation hotspots. In addition, it can be used to detect and visualize burst terms and betweenness centrality to identify emerging trends and radical changes, and turning points, respectively (Chen 2004; Chen 2006).

3.0 Empirical results

3.1 Publication analysis

The publication analysis is shown in Figure 1. Overall, the number of publications on VACC research exhibited an increasing trend during 1991-2017. More specifically, the period of 1991-2001 exhibited slow growth, with 210 related journal articles in eleven years. Then, the annual number of VACC studies in journal articles increased dramatically from forty-one articles in 2002 to 978 articles in 2017. Interestingly, the number of articles in the late twentieth century fluctuated dramatically between 1991 and 1999. This number declined abruptly from five in 1992 to one in 1993, then jumped to thirty-five and dropped to seventeen in the following four years before seeing a stable increase after 2001. These variations imply that VACC research did not receive continued and increasing attention from scholars until the new millennium. This period was considered

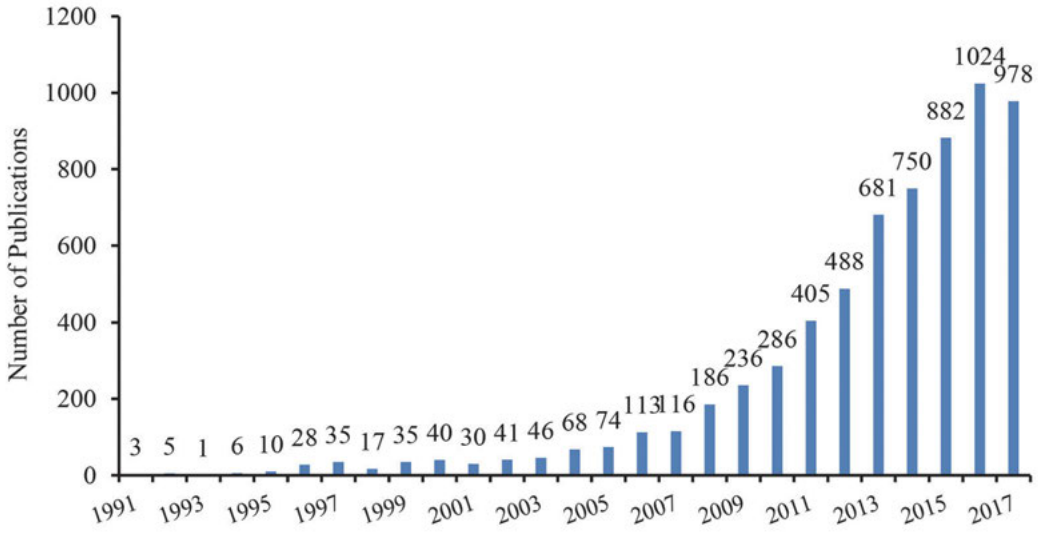

Figure 1. Number of publications in VACC area from 1991 to 2017.

representative because of the surge in vulnerability research following the 2001 IPCC report.

3.2 Subject categories and journals

The disciplinary composition of a given research field reveals the extent to which the research field is shaped by the confluence of disciplines and their respective roles. According to the database, the output data of publications on energy were distributed among more than 100 subject categories. Environmental sciences was the most common category (37.00% of all publications), followed by meteorology atmospheric sciences (16.50%), geosciences multidisciplinary (13.36%) and biodiversity conservation (7.35%). Other important disciplines include geography and civil engineering.

The 6,584 papers are published in more than 500 journals. *Climatic Change* ranks first in the number of publications (265, 4.02%), followed by *Natural Hazards* (171, 2.60%), *Global Environmental Change—Human and Policy Dimensions* (151, 2.29%), *PLOS One* (134, 2.04%) and *Regional Environmental Change* (134, 2.04%). Other important journals include *Global Change Biology Environmental Research Letters*, *Science of the Total Environment*, *Mitigation and Adaptation Strategies for Global Change* and *Environmental Science Policy*. The top ten most productive journals are leading journals in the field of VACC.

3.3 Major contributing countries/territories and institutions for the VACC field

Cooperation is an important component of scientific research and stems from the complexity of the problem, dynamics of knowledge growth and professionalism of domain knowledge. An individual scientist can seldom provide all of the expertise and resources necessary to address complex research problems (Hara et al. 2003). Therefore, we generated a network based on the authors' institutions and countries using CiteSpace. A timespan from 1991 to 2017 with a time slice of one year was selected for the analysis, and the top fifty most frequently occurring items from each slice were chosen. Figure 2 plots the co-occurrence relationship of countries/territories and institutes related to VACC research after simplification by Pathfinder network scaling. Together with the minimum spanning tree algorithm, this is a structural modeling technique commonly used to eliminate redundant or counterintuitive connections and retain the most salient ones (Samoylenko et al. 2006). The network consisted of 253 nodes and 352 links; each node represents a "country/territory" or "institute," and each link between them indicates their collaborative relations. A spectrum of colors indicates the temporal orders of co-occurrence links among countries or institutes, with the oldest in blue and newest in orange. The purple circles demonstrate key studies with a high centrality above 0.1, and a thicker circle shows a higher level of between centrality.

This figure illustrates that the major contributions in terms of total publication output primarily originate from the USA, England and Australia, which published more than 3,600 articles (54.85% of all publications), demonstrating strength in VACC research. Regarding the publication distribution, 2,111 papers are from the USA, followed by 752 from England, 748 from Australia, 596 from Germany, 543 from Canada, 454 from China, 385 from Spain, 358 from Italy, 358 from the Netherlands and 338 from France. Large numbers of VACC publications imply that

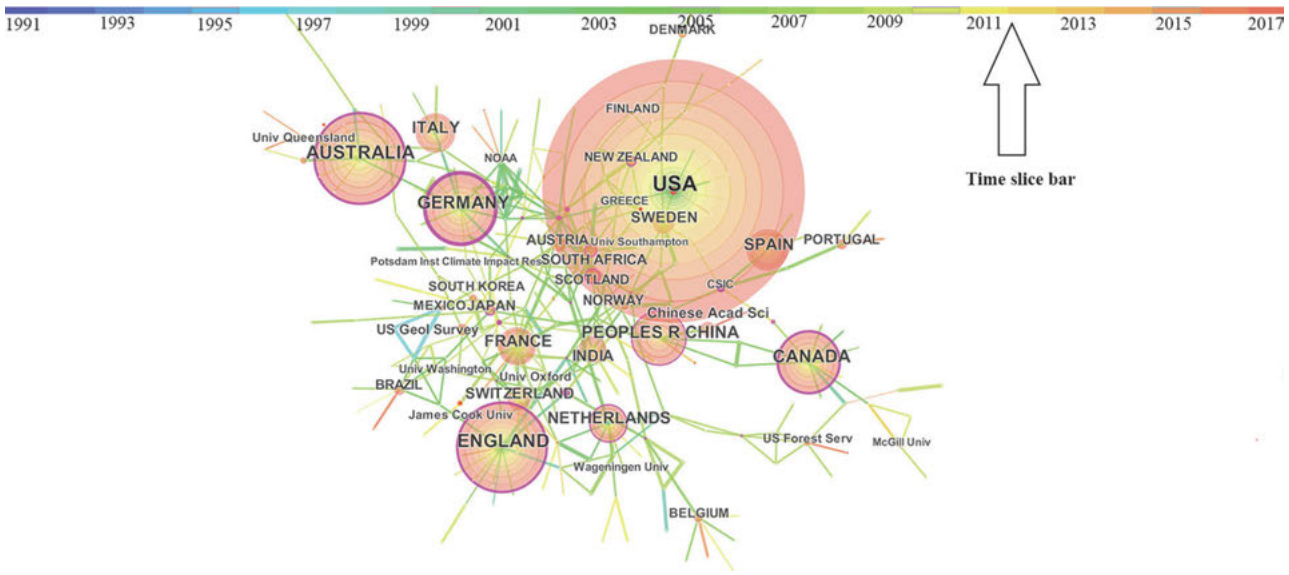

Figure 2. Research power network with 253 nodes and 352 links.

VACC has been widely established in these countries. Interestingly, England was the first country to participate in VACC research (in 1991), whereas the USA was the largest publication contributor.

In addition, Figure 2 identifies the contributions of and relationships among research institutions in the knowledge domain, as indicated by straight lines and circular nodes. Research progress is highly active at institutions in the USA, particularly from the U.S. Geological Survey (134 publications), U.S. Forest Service (eighty-nine publications), National Oceanic and Atmospheric Administration, NOAA (sixty-eight), Washington University (fifty-five) and Colmbia University (forty-five), followed by other productive institutions in various countries, including the University of Chinese Academy of Sciences, Queensland University (seventy-seven), Oxford University (seventy-four), James Cook University (seventy-four) and Wageningen University (fifty-nine). These institutions represent important publication centers for VACC research throughout the world and hold a dominant position in VACC research.

Moreover, identification of the nodes with high betweenness centrality indicates that Germany (0.42), England (0.25), Australia (0.21), Japan (0.20), Netherlands (0.18) and institutions such as Bayreuth University (Germany, 0.36), University of Aberdeen (England, 0.28), Harvard University (USA, 0.26), Council for Scientific Research, CSIC (0.25, Spain), University of Oxford (0.21, England) and University of Leeds (England, 0.18) have held key positions on the critical paths in the research power network and have played important roles in the development of VACC research.

Additionally, as indicated by bursts occurring within the past three years (2015–2017), the research outputs from such countries/territories as Greece and Taiwan of China as well as institutions, such as the University of Wisconsin (USA) and McGill University (Canada), are expected to continue to increase and be deserving of further attention in the future, as bursts are often followed by subsequent increasing trends. This analysis provides a significant first approach to understanding the diversity of VACC research and a preliminary basis for the selection of potential partners from among these countries and institutions.

3.4 Co-word analysis

Because keywords provide information about the core content of articles, a co-word analysis can be used to monitor research topics and evolving research frontiers of a knowledge domain. A timespan from 1991 to 2017 with a time slice of two years was chosen for the analysis, and the selection criteria was top fifty per-slice with global pruning by using the Pathfinder algorithm. The network consisted of 223 nodes and 119 links, as shown in Figure 3; each node indicates a "keyword," because the terms "climate*" and "vulnerab*" are used as search keywords, it is not surprising that "climate change" and "vulnerability" have the largest frequencies of 3,293 and 1,837, respectively. Other high frequency keywords include "adaptation" (1111), "impact" (962), "model" (688), "management" (640), resilience (487), "temperature" (420), "variability" (419), "risk" (417), "adaptive capacity" (414), "United States" (385), "framework" (354), "climate" (352), "conservation" (350), "system" (333), "drought" (321) and "biodiversity" (308). These abovementioned keywords have all been topics of interest in VACC research in the past twenty-seven years.

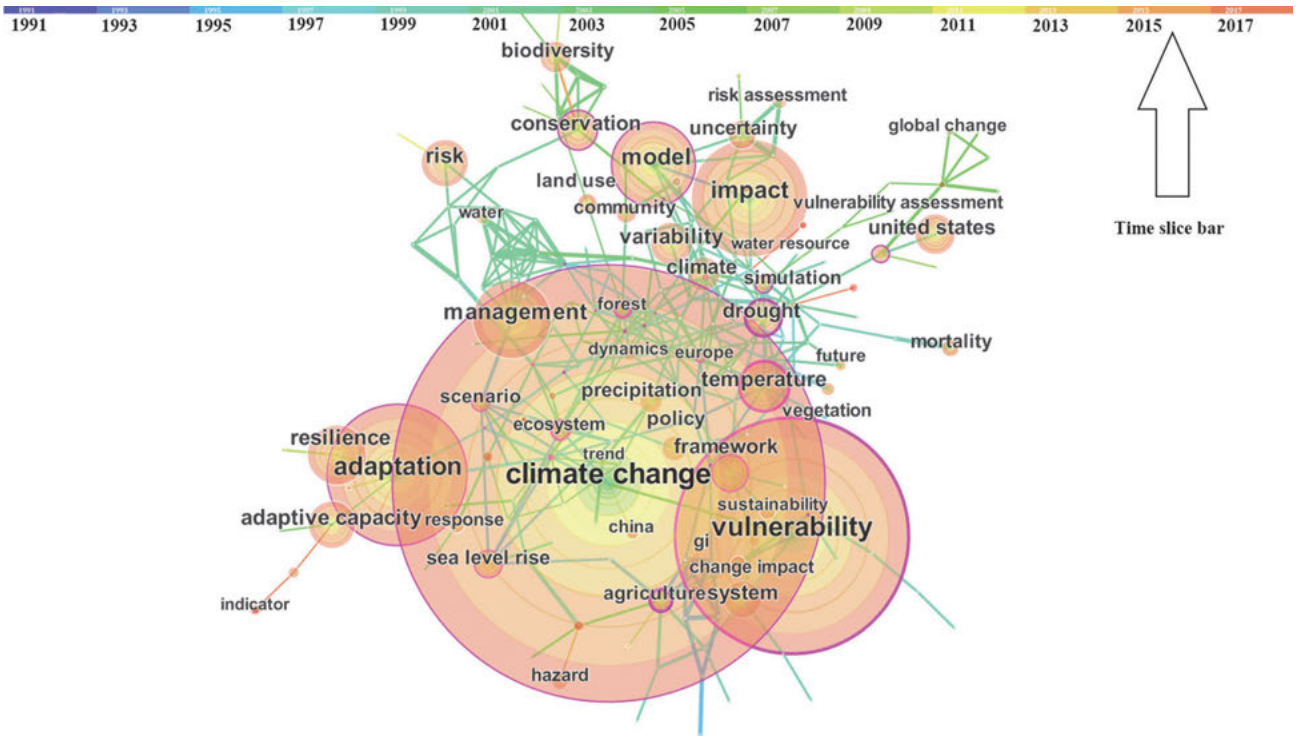

Figure 3. Keyword co-occurrence network from 1991 to 2017.

Purple rims of nodes, which indicate pivotal points with high betweenness centrality (≥0.1), tend to be intellectual turning point keywords. As shown in Figure 3, among the keywords with purple circle, "climate change" had the highest centrality (1.16), followed by "model" (1.15), "agriculture" (0.75), "sea-level rise" (0.72), "precipitation" (0.65), "uncertainty" (0.64), "United States" (0.62), "drought" (0.61), "trend" (0.61) and "simulation" (0.60). Therefore, VACC research widely studied the use of the "model" and "simulation" methodologies to assess the vulnerability of agriculture to climate change.

Burst detection can identify burst keywords as indicators of emerging trends (Chen et al. 2014). Keywords with citation bursts mean that this topic received particular attention in academic circles during a certain period. Figure 4 shows the top sixty keywords with red inner rings, which indicate when the frequency changed the most from 1991 to 2017. In particular, the keywords with the strongest burst in the past three years (2015-2017) represent the emerging trends in the VACC field.

Between 1991 and 2000, the keywords of higher strength were the "sea-level rise" (strength is 11.41), which experienced a burst from 1996 to 2008, and "pattern" (20.00), which experienced a burst from 1999 to 2012. Then, the focus was on specific aspects and diverse approaches that aim to enhance the performance of VACC, such as "Africa" (15.29, 2003-2014), "distribution" (15.66, 2005-2010), "food security" (19.33, 2009-2012), "social ecological system" (16.45, 2010-2012), "flood" (15.70, 2011-2012), "growth" (20.14, 2011-2014), "resource" (15.19, 2013-2014) and "science" (15.57, 2013-2014). These keywords were the topics of interest for VACC research in the past twenty-five years (1991-2014). In the past three years (2015-2017), publications with the keywords "indicator," "ecosystem service" and "climate change adaptation" increased dramatically, implying that these keywords are becoming the current research hotspots or emerging trends in the VACC field.

3.5 Research clusters in the VACC research field

A document co-citation network is a network of co-cited references and is useful in studies of the structure, dynamics, and paradigm developments of a given research field (Liu et al. 2015). Co-citation cluster analysis for highly cited papers could reveal the underlying intellectual structure of a given scientific field and provide beneficial information for scientific edge cutting spots (Liu and Chen 2012). Based on 254,642 academic documents cited in the 6,584 records from 1991 to 2017, we selected the top fifty most cited or occurring items from each two-year time slice with global pruning by using the Pathfinder algorithm. In addition, to clarify the development paths of the thirteen clusters and visualize the emerging trends represented by their principal documents, a co-citation timeline visualization was generated based on the different sizes of

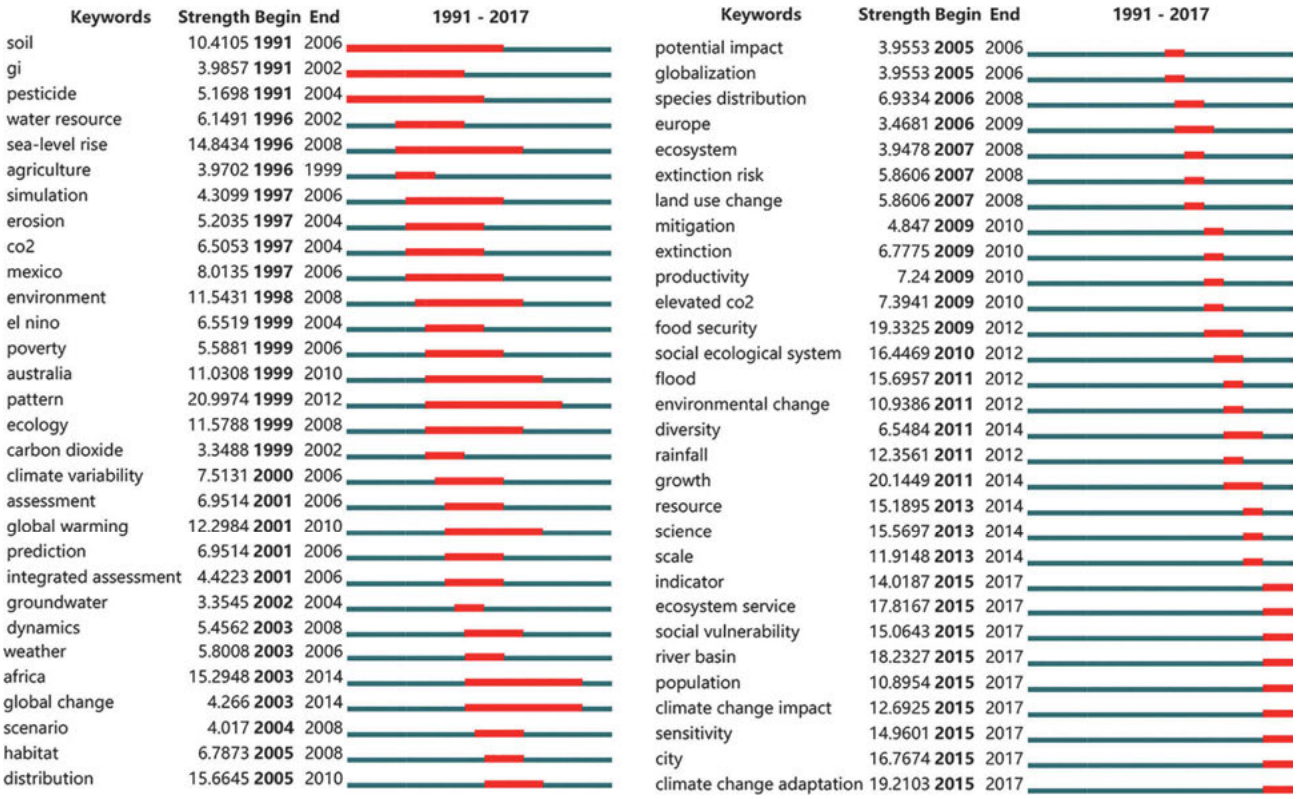

Figure 4. Top sixty keywords with the strongest citation bursts from 1991 to 2017.

the nodes and the evolution of the cluster colors (see Figure 5). This network is comprised of 581 nodes and 1,541 links; 106 clusters were generated with a modularity Q of 0.8607 and a mean silhouette of 0.3016. Each node represents one cited document; a larger node indicates a higher total co-citation frequency of the associated reference. The link colors correspond directly to the time slice, which means that the cold colors represent the early years and the warm colors represent the more recent years. Furthermore, the homogeneity of each cluster is measured by a silhouette score ranging from negative one to one, where a value of one represents a perfect separation from other clusters. The quality of the overall division is measured by the modularity Q, which ranges from zero to one. A high modularity may imply a well-structured network (Chen 2004, 2006; Chen et al. 2009). The most cited document in each of these clusters was identified to describe the characteristics of these clusters; the clusters in this research are labeled by index terms from their own citers. The most active citing papers represent research fronts (Chen et al. 2014). A research cluster can be recognized as a new emerging trend if contains a certain number of articles with citation bursts (Chen et al. 2014).

As illustrated by Figure 5 and Table 1, the top thirteen clusters all have a high silhouette value (ranging from 0.836 to one), indicating that each cluster is fairly homogeneous. These thirteen largest clusters cover 69.19% of the 581 nodes. The largest seven clusters with more than thirty nodes, covering 48.88% of all nodes, are summarized in Tables 1 and 2. Each mean year provides a typical period of research time distribution. Purple node rims (see Figure 5) that indicate pivotal points with high betweenness centrality (≥0.1) tend to be intellectual turning point documents.

We first analyze the largest knowledge base clusters of VACC research. The largest cluster (#0) has sixty-four members and a silhouette value of 0.882, indicating high consistency among the cited articles in this cluster, largely published around 1998. This cluster is labeled "understanding" by LLR. The most active citer (Parson et al. 2003) to the cluster is 0.28. This paper proposes a program of research and analysis to advance the capability for the assessment of climate impacts, vulnerabilities and adaptation options, identifies three specific priorities for improvement in climate impact assessments and proposes an institutional model for assessment. Adger (2006) has the highest betweenness centrality (0.47) and is the most highly cited document (see Table 2). This paper is the important knowledge base of cluster two as well as an intellectual turning point. The paper argued that social vulnerability should be given priority in assessments of the impacts of climate change and climate extremes. Adger out-

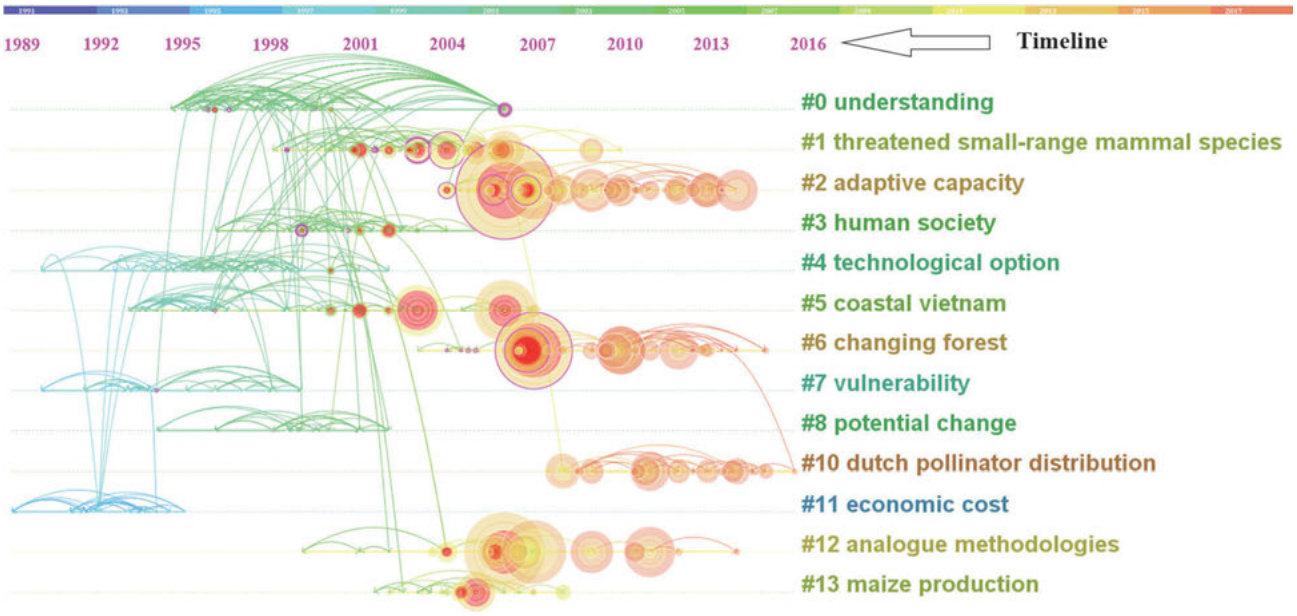

Figure 5. Co-citation timeline visualization of the 13 clusters.

Cluster ID	Size	Silhouette	Label (LLR)	The most active citing publication
0	64	0.882	understanding	Parson et al. (2003)
1	40	0.961	threatened small-range mammal species	Morueta-Holme et al. (2010)
2	39	0.997	adaptive capacity	Ford et al. (2010).
3	38	0.903	human society	Ziervogel and Calder (2003)
4	36	0.836	technological option	Klein et al. (2001).
5	34	0.882	coastal Vetnam	Adger (1999)
6	33	0.978	changing forest	Fettig et al. (2013).

Table 1. The seven largest clusters sorted by size.

Cluster ID	Cited publications	High Centrality publications	Mean (Year)
0	Adger (2006); Smit et al. (2000); IPCC (1995)	Adger (2006); Broecker (1997); Watson (1995)	1998
1	Parmesan (2006); Thomas et al. (2004); Elith et al. (2006)	Parmesan and Yohe (2003); Brooks et al. (1999); Peterson et al. (2002)	2003
2	Smit and Wandel (2006); IPCC (2007); Adger et al. (2009)	Ford and Smit (2004); Smit and Wandel (2006); Folke (2006); Nelson et al. (2007)	2009
3	Yohe and Tol (2002); IPCC (2001); Adger (1999)	Adger (1999); Church et al. (2001); Shaw et al. (1998)	2000
4	O'Brien and Leichenko (2000); Klein and Nicholls (1999); Stern and Easterling (1999)	Nicholls (1995); Klein and Nicholls (1999); Raper et al. (1996)	1996
5	Füssel and Klein (2006); Turner et al. (2003); IPCC (2001a)	Cutter (1996); Ribot et al. (1996); Adger (1999)	1998
6	IPCC (2007b); IPCC (2007a); Moss et al. (2010)	Holman et al. (2005); Webster et al. (2005); Nicholls (2004)	2009

Table 2. The three most active cited and high centrality publications in the largest seven clusters.

lines a framework for analyzing social vulnerability and conducts an empirical study in coastal northern Vietnam. The two highly cited papers focus on climate change impact assessment (IPCC 1996a) and adaptations to climate change (Smit et al. 2000), whereas the two studies with strong betweenness centrality focus on the characteristics of climate change (Broecker 1997; IPCC 1996b). Cluster zero focuses on climate impact assessments and adaptations to climate change.

The second largest cluster (one) contains forty articles and has a silhouette value of 0.961, with the studies largely published around 2003. This cluster is labeled "threatened small-range mammal species" by LLR. The most active citer (Morueta-Holme et al. 2010) to the cluster is 0.17; this paper uses species distribution modeling to assess the climate sensitivity, climate change risks and conservation implications for a threatened small-range mammal species. The top three intellectual-based papers (Parmesan 2006; Thomas et al. 2004; Elith et al. 2006) focus on the distribution of species, such as plants and animals, in the context of climate change. The three most active high centrality publications use different methods to predict the possible impact of climate change on species diversity and distributions (Parmesan and Yohe 2003; Brooks et al. 1999; Peterson et al. 2002). Cluster one focuses on the vulnerability of species distribution and diversity to climate change.

Cluster (two) contains thirty-nine articles and has a silhouette value of 0.997, with the studies largely published around 2009. This cluster is labeled "adaptive capacity." The most active citer (Ford et al. 2010) to the cluster is 0.15; this document examines the importance of case study and analogue methodologies in identifying opportunities to reduce vulnerability and enhancing adaptive capacity to climate risks. Smit and Wandel (2006) is the most highly cited document in cluster two and has the largest citation ring, with 208 citation counts in VACC research (Figure 4). In addition, it has a high betweenness centrality (0.16). This ground-breaking article reviews the concept of adaptation of human systems to climate change, highlighting that adaptations in human communities are closely associated with adaptive capacity and vulnerability. The other two highly cited documents (IPCC 2007; Adger 2009) in cluster two also focus on the role of socio-economic contexts, including values and ethics, risk, knowledge and culture in adapting to climate change and reducing vulnerability. In addition, Ford and Smit (2004) has the highest betweenness centrality (0.18); these researchers define vulnerability as a function of exposure to climatic stresses and the adaptive capacity to cope with these stresses and develop a conceptual model of vulnerability. In addition, the resilience is introduced as a new perspective to analyze adaptation processes and understand the dynamics of social–ecological systems (Folke 2006; Nelson et al. 2007). The two articles are also important intellectual turning points in cluster two. In general, cluster two focuses on adaptive capacity and resilience studies addressing the vulnerability of climate change.

The fourth largest cluster (three) is labeled "human society." It has thirty-eight members and a silhouette value of 0.903, with the studies mainly published around 2000. The most active citer is the work of Ziervogel and Calder (2003), which assesses the vulnerability of rural livelihoods to climate change. This research bridges macro-level variability with local-level impacts and adaptation to provide insights into the dynamics of forecast use and impact among vulnerable groups. Yohe and Tol (2002) is the most cited document in cluster three. This paper offers a method for evaluating systems' abilities to handle external stress. The method helps to productively distinguish between macro- and microscale factors that work to define the underlying determinants of coping capacity. Adger (1999) has the highest betweenness centrality (0.21) and is a highly cited document. In contrast to the predominant views on vulnerability regarding the impacts of climate change, which concentrate on the physical dimensions of the issue, this paper emphasizes the social dimensions of vulnerability. Cluster three focuses mainly on the vulnerability of human societies, particularly vulnerable groups, to climate change.

The fifth largest cluster (four) is labeled "technological option." It has thirty-six members and a silhouette value of 0.836, with the studies largely published around 1996. The most active citer is Klein et al. (2001); this article highlights the role of technologies in reducing vulnerability to climate change in coastal zones. O'Brien and Leichenko (2000) have the most-ited document in cluster four; their research considers the joint impacts of two global processes, climate change and economic globalization, and introduces the concept of double exposure as a framework for examining the simultaneous impacts of these processes. The other two highly cited documents (Klein and Nicholls 1999; Stern and Easterling 1999) examine technologies for and approaches to climate change prediction and vulnerability assessment in coastal areas. Nicholls (1995) and Raper et al. (1996), with a high centrality, focus on estimating future temperature changes and sea-level rise and the possible effects of these processes in coastal areas. Cluster four focuses on the study of climate prediction, impacts and adaptations in coastal areas.

The sixth largest cluster (five) is labeled "coastal Vietnam" and has thirty-four members and a silhouette value of 0.882, with the studies largely published around 1998. The most active citer is the article by Adger (1999), who emphasizes the social dimensions of vulnerability and finds that social vulnerability is influenced by institutional

and economic factors in coastal northern Vietnam. The most cited publications in cluster five are by Füssel and Klein (2006), who demonstrate the evolution of vulnerability assessments and divide it into four stages: climate impact assessment, first- and second-generation vulnerability assessment, and adaptation policy assessment. Turner et al. (2003) present a vulnerability framework for assessing coupled human-environment systems. This framework emphasizes that vulnerability is influenced by exposure to hazards (perturbations and stresses) as well as the sensitivity and resilience of the system experiencing such hazards. The framework is conducive to the development of vulnerability assessments at different scales, including place, region and world. IPCC (2001a) summarizes the milestones in the field of international climate change research, which provide a wealth of knowledge for climate change vulnerability assessments. In addition, the two intellectual turning point documents (Cutter 1996; Ribot et al. 1996) focus on social vulnerability assessment under environmental hazards and climate change settings. Cluster five focuses mainly on social vulnerability assessments under multidimensional stressors and physical and socio-economic shocks.

The seventh largest cluster (six), labeled "changing forest," has thirty-three members and a silhouette value of 0.978, with the studies mainly published around 2009. The most active citer is the article of Fettig et al. (2013); this paper finds that the forest ecosystems in western North America are becoming increasingly vulnerable due to climate change. The top three intellectual-based papers summarize the key scientific findings of the Intergovernmental Panel on Climate Change report and present detailed analyses of the benefits and costs of various methods of mitigating and preventing climate change. The paper by Holman et al. (2005) has the highest betweenness centrality (0.14) in cluster six; this paper developed a methodology called "Drivers-Pressure-State-Impact-Response" (DPSIR) for regional climate change impact assessment that provides a structure for linking the modeling and scenario techniques. Webster et al. (2005) investigate changes in the number, duration and intensity of tropical cyclones in a warming environment. Nicholls (2004) studies the coastal floods changes under the SRES climate and socio-economic scenarios. Cluster six focuses mainly on climate change vulnerability assessments on a local/regional scale.

3.6 Author co-citation network

The co-citation network of the thirty most-cited authors in each time slice after being simplified using the Pathfinder algorithm is shown in Figure 6. The network consists of the 203 most cited contributors and 254 co-citation links and can identify the interconnections among individual authors in the VACC research field. The node size represents the total number of citations for the relevant authors. Nodes with purple rings act as bridges in the de-

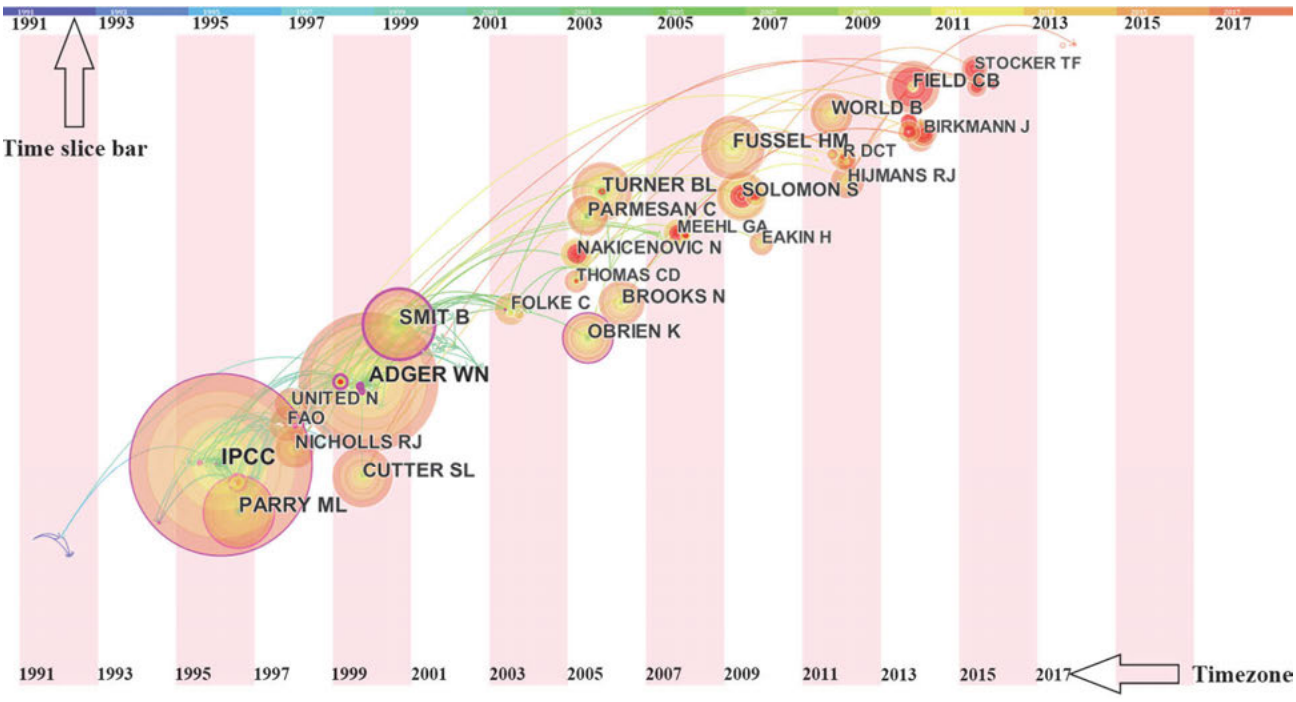

Figure 6. Author co-citation network with 203 nodes and 254 links.

velopment of VACC scientific field linking research in different time periods. A highly cited author is not necessarily a scholar with high betweenness centrality. Nodes are only likely to become a leading scholar with a significant impact on the development and evolution of VACC research when they have both high citation and high betweenness centrality.

In addition, some nodes in Figure 6 have red inner rings, which means that the number of citations increases rapidly over a period of time. The work of these authors will likely have far-reaching implications for the future of VACC research; therefore, their work deserves more attention. In the past five years (2013-2017), the most striking case is Storker (University of Bern), a Swiss climate scientist, who has the highest burst strength (56.52). Storker's research focuses on the development of climate change models based on the analysis of ice cores from the polar regions. In a 2015 paper, he claimed that the ocean in the Earth system, as a vital service provider, is suffering from the profound impact of climate change, and its physical state and the health of its ecosystems must be further evaluated (Stocker 2015). The researcher with the second highest burst strength, Field, is from Stanford University, and his research focuses on the responses of ecosystems to global climate change and plant ecophysiology. His work has been widely cited in the field of VACC research in the past five years. In particular, the article published in *Science* received considerable attention from researchers. The article holds that the rate and magnitude of climate change that terrestrial ecosystems ultimately experience will critically depend on human decisions, innovation and economic development, which will in turn determine the pathway of greenhouse gas emissions (Diffenbaugh and Field 2013). Furthermore, the researcher with the third highest burst strength is Hulme (University of Cambridge), with bursts of 46.39; he specializes in the compilation and analysis of global climate datasets and the construction and application of climate change scenarios for impact, adaptation and integrated assessment. His work explores the concept of climate change using historical, cultural and scientific analyses, seeking to illuminate the numerous ways in which climate change is deployed in public and political discourse. The researcher with the fourth highest burst strength is Wilby (Loughborough University), with bursts of 29.44; his latest research is exploring smarter approaches to climate risk assessment and decision-making under deep uncertainty about the future climate. This research shifts the focus to better understanding and then managing the climate vulnerability of human and natural systems. The four other authors with high bursts are Hallegatte (33.61, World Bank), Pearson (30.15, University of Kansas, USA), Birkmann (20.93, Universität Stuttgart, Germany) and Barnett (16.31, University of Melbourne, Australia). In general, the works of these authors provide important insights and theories for the latest VACC research and help to probe the direction of future VACC research.

The top ten most frequently cited authors are listed in Table 3. IPCC, the international body for assessing the science related to climate change, was the most frequently cited. IPCC can provide policymakers with regular assessments of the scientific basis of climate change, its impacts and future risks, and options for adaptation and mitigation. IPCC provides a wealth of important information for

Author	Frequency	Centrality	Employer institution
IPCC	1304	0.17	World Meteorological Organization, WMO; UnitedNationsEnvironmentProgramme, UNEP
Adger	985	0.12	University of Exeter, England
Smit	547	0.29	University of Guelph, Canada
Parry	538	0.12	Imperial College London, England University of East Anglia, England
Cutter	475	0.03	University of South Carolina, USA
Füssel	462	0.02	European Environment Agency (EEA), Denmark.
Turner	443	0.02	Arizona State University, USA
O'Brien	384	0.08	University of Oslo, Norway
Brooks	373	0.03	International Union for Conservation of Nature, Switzerland
Solomon	366	0.03	Martin Professor of Environmental Studies (MIT), USA

Table 3. The profile of the top ten most co-cited pioneers. *Source:* Web of Science and personal web pages.

VACC research, particularly a new set of technologies, methods and frameworks for vulnerability assessment. The second most cited author is Adger, who is a professor of human geography and whose research includes global environmental change, vulnerability and adaptation to climate change and the political economy of the environment. Smit is the third most cited and has the highest centrality among the listed authors in Table 3, suggesting that his work is more groundbreaking in overall VACC research. He focuses on the vulnerability and adaptations of communities and socio-economic systems to global environmental changes, particularly climate change. Smit's recent and current projects include vulnerability and adaptive capacity of communities in the Arctic in the face of climate and socio-economic conditions and impacts and adaptation to climate change in developing countries.

Parry is a climatologist; until 2008, he was the co-chair of working group II (Impacts, Adaptation and Vulnerability) of the IPCC. Cutter is a geographer, and her primary research interests are in the area of disaster vulnerability/resilience science and how vulnerability and resilience are measured, monitored, and assessed. Füssel's primary area of research is climate change, impacts and vulnerability in Europe. Turner is a sustainability scientist, and his research specialisms including land use and land cover, ecosystem services, hazards assessment, risk and vulnerability. O'Brien's research explores the ways that such processes as climate change, biodiversity loss and other large-scale environmental transformations interact with other global processes to exacerbate inequity, increase vulnerability and undermine sustainability. Brooks is an ecologist, geographer, and ornithologist, and his areas of expertise include biodiversity conservation and species extinction. Solomon is an atmospheric chemist who focuses on the study of climate change and its coupling to chemistry and comparative studies of environment and society. Overall, the works of these authors are an important knowledge domain for VACC research and are critical to better understanding the evolution and trends of VACC research.

4.0 Conclusions

In this article, we collect bibliometric data from 6,584 journal articles from the WoS core collection database and examine the knowledge domain and emerging trends in VACC research using co-word analysis and co-citation methods via the bibliometric software CiteSpace. The findings demonstrate that VACC research has gradually drawn the attention of international scholars from 1991 to 2017, particularly during the period of 2001-2017, and that the number of corresponding publications has increased continuously and will continue to grow in the near future. Environmental Sciences (37.00% of all publications) is the most common category of these publications. *Climatic Change*, *Natural Hazards*, *Global Environmental Change* are the top three most productive journals that are leading journals in the fields of VACC. The major contributions, in terms of total publication output primarily originate from countries in Europe (England, Germany, Spain, Italy, Netherlands and France) and North America (USA and Canada). Other highly productive countries include China, India, and institutions, such as University of Chinese Academy of Sciences, U.S. Geological Survey and U.S. Forest Service, are also the highly productive in VACC research. In addition, certain countries, such as Germany and England, and institutions, such as Bayreuth University, University of Aberdeen and Harvard University, occupied key positions on the critical paths in the research power network and have played important roles in the development of VACC research.

The results of the co-word analysis indicate that "adaptation," "impact," "model" and "management" have been the main keywords in VACC research over the past twenty-seven years. Furthermore, the use of "climate change adaptation," "river basin," "ecosystem service," "city" and "social vulnerability" as keywords increased dramatically in the last three years (2015-2017), implying that they are becoming the current research hotspots or emerging trends in the VACC field. In addition, co-citation investigation revealed the intellectual structure of the research trends relevant to worldwide VACC research. The articles with high citations and high centrality, published by Smit (2006), Adger (2006), Solomon (2007), Füssel (2006, 2007), Parry (2007) and Turner (2003), provide the fundamental concepts, techniques and methods for VACC research and play important roles in the development of VACC research. In addition, seven typical clusters were identified based on the cited publications, and the focuses of these clusters can be divided into five topics: climate impact assessment and adaptability; species vulnerability in the context of climate change; human adaptability and resilience in the context of climate change; social vulnerability in the context of climate change; and vulnerability assessments of different ecosystems at multiple scales in the context of climate change.

Additionally, based on the author co-citation analysis, considerable attention should be paid to the works of authors with high citations, such as Adger, Smit, Parry, Cutter, Füssel, Turner and O'Brien, and to authors with strong citation bursts in the past three years, such as Stocker, Field and Barnett, because of their fundamental influence on the development and evolution of VACC research, and because their work will likely have far-reaching implications for the near future of VACC research.

In summary, we conducted a comprehensive analysis of VACC research conducted worldwide during 1991–2017

using a mainstream co-citation analysis tool, CiteSpace. The results in this paper can provide an effective and rapid overview for research students and "newcomers" to the VACC field and a more comprehensive picture of its overall intellectual development without having to analyze hundreds of studies in detail. Moreover, this study may help VACC scholars in exploring the critical research that may serve as fundamental sources of inspiration for proposing new research issues and building new perspectives.

However, in the construction of any bibliometric map, some biased decisions and acts of interpretation are always involved (Mazzocchi 2018). For example, we retrieved papers solely using the WoS core database with the document types of article and review to obtain uniform references for CiteSpace analysis. In this case, the limited scope of data collection may have underrepresented publications in this domain, while some other document types such as monographs, edited books, reports, and conference proceedings may be valuable for analysis (Nederhof 2006), meanwhile, the coverage of languages also causes intractable problems for bibliometrics (Bouchard et al. 2015). This exercise also demonstrated that relevant records could be missing if the query phrases for topic search do not appear in titles, abstracts and keywords (Kim et al. 2014).

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