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TOPICAL REVIEW

Vulnerabilities—bibliometric analysis and literature review of evolving concepts

Carlo Giupponi[1,3] **and Claudio Biscaro**[2]

[1] Venice Centre for Climate Studies, Department of Economics, Ca' Foscari University, Venice, Italy
[2] Institute for Organisations and Global Management Studies, Johannes Kepler Universität, Linz, Austria
[3] Author to whom any correspondence should be addressed.

E-mail: cgiupponi@unive.it **and** Claudio.Biscaro@jku.at

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Abstract

In this work we analyse the evolution of the vulnerability concept in the research streams of climate change adaptation (CCA) and disaster risk reduction (DRR). We combine a traditional literature review with data mining procedures applied to bibliographic databases to reconstruct the history of the concept within various research topics, showing its evolution and convergences over time. To do that, we integrate different methods combining machine learning algorithms with network and cluster analyses to examine a set of 3757 articles, analysing their distinctive features and similarities on the basis of their contents as well as co-authorships. Bibliometric analyses enable the identification of different communities of articles, pinpointing key papers and authors, while literature review makes it possible to assess the concept of vulnerability evolved within and beyond research communities and scientific networks. Moreover, this work examines the role played by documents published by UN institutions (UNDRO, UNISDR, IPCC) in contributing to the evolution of vulnerability and related concepts. Results show that signs of convergence are evident between the two research streams, and that the IPCC reports have played a major role in proposing solutions for unifying definitions of vulnerability. We observe that the phases of preparation of the IPCC reports are very rich in methodological and terminological developments, while after publication, the literature shows evident signs of propagation of the proposed concepts. The DRR research stream developed before the research stream on CCA, but the latter flourished rapidly and became much larger in terms of number of publications. Nevertheless, in terms of contents, adaptation studies and the IPCC have shown increasing adoption of the concepts developed within the disaster research stream, in particular with regard to the interpretation of vulnerability as one of the dimensions of risk.

1. Introduction

In 2006, Neil Adger published a paper titled 'Vulnerability', in which he explored the 'research traditions of vulnerability to environmental change' and the related challenges for future research [1]. He acknowledged the diversity of epistemologies and methods in different research streams, but he considered it an advantage rather than a problem, and identified common and distinctive features. That paper inspired our work, but we preferred to use the plural form in our title, and the reasons for our choice should become evident from the text below.

In the same journal issue, Janssen and colleagues published a work that explored scholarly networks on vulnerability as well as resilience and adaptation ([26]; updated in [25]), and observed scholars' increasing interest in the three topics, and the signs of increasing overlapping of knowledge domains. In the same year, Thomalla and others [34] analysed the research communities dealing with vulnerability and focused in particular on two of them, defined as

disaster risk reduction (DRR) and climate change adaptation (CCA), pointing out that until then those communities had mainly worked in isolation[4].

The vulnerability literature is vast and at the core of several research streams across environmental and socio-economic disciplines, in some cases strictly linked to the two mentioned above, such as sustainability science, or less related to them, such as health and medical sciences and this brings to a plethora of often contrasting definitions of the term. Moreover, the usefulness of the term is even questioned by some authors who cast doubts on its cultural and political implications. Worth mentioning are the works by Hewitt, who wrote that 'Vulnerability may be an unfortunate term' ([18] p 82), as it may encourage individuals and communities to adopt a passive attitude towards somehow given social pathological conditions to be treated with professional interventions, thus neglecting the existing capacities. Bankoff [2] further develops upon Hewitt's ideas. He warns us against reducing vulnerability to a 'formulaic expression' without adequate consideration of local culture, knowledge and coping practices to prevent the concept from becoming part of a Western discourse that denigrates large parts of the world.

Even if the vulnerability framing is not universally adopted and alternatives are available (e.g. resilience), recent years have brought to the fore a flourishing scientific literature on vulnerability and global change. In parallel, international institutions published a series of important reports, which contributed significantly to the evolution and consolidation of the vulnerability concept. In the case of CCA, an important contribution was made by the reports of the Intergovernmental Panel on Climate Change (IPCC), in particular, the Assessment Reports, the last of which (AR5) has been recently released in its various components[5]. Vulnerability is at the core of the interests of Working Group 2 (WG2) on 'Impacts, Adaptation and Vulnerability'. At the time of the references cited above, the AR4 ([22]; p 883) proposed a carefully articulated and precise definition: 'Vulnerability is the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity'. Nevertheless, later on, the WG2 Glossary of the AR5 ([24]; p 1775) included a revised—and vaguer—definition of vulnerability as 'the propensity or predisposition to be adversely affected', adding also that it 'encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt'. This new definition seems to acknowledge the challenge of developing a widely accepted, precise and operational definition of vulnerability. Interestingly for our purposes, a footnote to that entry in the Glossary states that the definition differs from the one provided in the previous AR and other IPCC reports to reflect 'progress in science'.

Similar to the IPCC for climate change research is the role played for disaster studies by the United Nations International Strategy on Disaster Reduction (UNISDR), and, before 1999, in the United Nations Disaster Relief Office (UNDRO). In 1980 UNDRO published a report on Natural Disasters and Vulnerability Analysis cited in most of the disaster literature on vulnerability in earlier times ([36], p 5) proposing the following definition: 'the degree of loss to a given element at risk or set of such elements resulting from the occurrence of a natural phenomenon of a given magnitude and expressed on a scale from (no damage) to 1 (total loss)'. In 2009 UNISDR published a terminology booklet [37]; p 30), in which vulnerability is redefined as the 'characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard'. UNISDR does not have a specific focus on climate change and thus does not refer to it in the definition of vulnerability, but it does however move the focus of the definition from 'system' to 'community'. While a system can indeed be made of any kind of interacting elements, a community identifies sets of individuals, theoretically not only humans, with a clear social connotation. Further comments added to the UNISDR definition clarify that the focus is on humans and their societies, in which vulnerability may emerge from different combinations of 'physical, social, economic, and environmental factors', independently of the community's exposure, i.e. what is in fact present in hazard zones and thus subject to potential losses ([37]; p 15).

The definitions proposed by CCA and DRR communities have evolved autonomously, and have divergent emphases and formulations, but in recent times efforts have been made to favour coordination and integration. In its 2012–25 Work Programme UNISDR set four objectives, three of which are intended to improve coherence with CCA and jointly strengthen decision making and investments in both fields [38]. In parallel, IPCC launched the effort for the development of the SREX Report (IPCC Special Report on 'Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation'; [23]), in which authors belonging to both communities worked together to develop a coordinated approach for CCA and disaster risk, and proposed a definition of vulnerability (p 564) to be adopted later on by the AR5.

From the above it appears that the concept of vulnerability is still experiencing an on-going evolution,

[4] The notion of vulnerability, as we will discuss later, plays a crucial role in several disciplines, such as development studies, sustainability science, human health, relief management, etc. Therefore, the two research communities we focus on are not the most relevant in general, but they can be considered as those of greatest interest in global change studies.

[5] See www.ipcc.ch/report/ar5/.

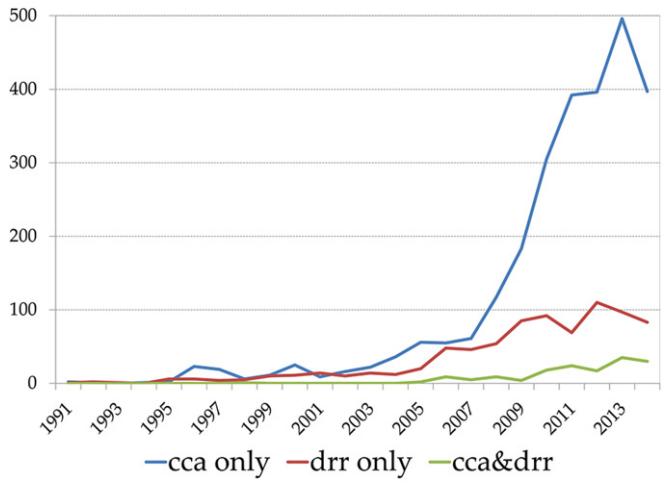

Figure 1. Number of publications per year in the climate change adaptation (CCA) and disaster (DRR) research communities and in the intersection of the two (CCA&DRR).

and also that several efforts are in place to facilitate the convergence of research communities. In this paper we aim to explore those developments through a traditional literature review supported by the opportunities for bibliometric analysis offered by bibliographic databases and data mining techniques.

The paper is organized as follows. Section 2 introduces the set of methods of bibliometric and content analysis applied to the datasets of papers extracted from the ISI Web of Science database. Section 3 presents the results of our analysis and in particular (i) the bibliometric analysis of paper contents, and of authorships and co-authorship networks; and (ii) the review of the literature analysed using bibliometric methods, with a focus on the key papers contributing to the evolving concept of vulnerability in the disaster and CCA literature streams. Section 4 discusses the main results and concludes the paper.

2. Materials and methods

2.1. Data

To obtain our data, we searched the ISI Web of Science™ database (WoS) (last access on 17 November 2014) and created two separate datasets searching exclusively for (i) climat∗ chang∗ adapt∗ and vulnerability, and (ii) disaster∗ risk∗ reduc∗/hazard∗ and vulnerability, which returned 2795 and 962 results, respectively. The two groups broadly mirror the communities described by Thomalla and others [34]. Overall, we identified three categories of article. Records exclusively part of the first search were categorized as 'CCA' and numbered 2639 articles; 800 articles were exclusively part of the second search and were labelled 'DRR'; 155 articles appeared in both searches and produced a third set labelled as 'CCA&DRR'.

As figure 1 shows, the steady increase in the number of publications per year highlights the vibrant activity in both communities, especially in the CCA research stream[6]. Around 2006 both fields of literature published some 50 new papers related to vulnerability per year, but while adaptation literature revealed a booming interest in the topic, reaching approximately 500 articles per year in 2013, the disaster literature has fluctuated at around 100 new articles per year since 2009. As for the CCA studies, after 2006 there has been a growing number of articles across the two communities. It is interesting to explore whether this phenomenon represents a sign of cultural contamination and convergence between the two communities.

2.2. Bibliometric analysis

2.2.1. Identification of seminal papers and topics

In analogy with the analyses carried out by Janssen *et al* [26], we used HistCite™ to analyse the network of paper citations and to identify those that could be considered seminal for the two communities, i.e. the works receiving the highest number of citations within each research stream. The results of the top five papers in terms of citations are reported in table 1. We then searched the two original datasets for papers having the words defin∗ or concept∗ in the title or abstract to identify those that, even if not highly cited, may have contributed to the development of the concept and definition of vulnerability. We thus obtained two lists of approximately 40 papers of potential interest for the review of the literature, further expanded during the analysis of their contents by including the references that appeared more frequently in the citations, in particular, books and documents of international institutions, not included in the WoS database.

[6] It is to be noted that the decrease in 2014 must be attributed to the timing of the search, which has been carried out before the end of the year.

Table 1. Top-5 papers in terms of citations within the disaster risk reduction (DRR) and climate change adaptation (CCA) literatures, according to HistCite™.

	Paper	Citations
DRR		
1	Wisner B, Blaikie P, Cannon T and Davis I 2004 At Risk: Natural Hazards, People's Vulnerability and Disasters 2nd edn (New York: Routledge)	143
2	Blaikie P, Cannon T, Davis I and Wisner B 1994 At Risk: Natural Hazards, People's Vulnerability and Disasters (Taylor and Francis)	121
3	Cutter S L, Boruff B J and Shirley W L 2003 Social vulnerability to environmental hazards *Soc. Sci. Q.* **84** 242–61	92
4	Cutter S L 1996 Vulnerability to environmental hazards *Prog. Hum. Geogr.* **20** 529–39	70
5	Adger W N 2006 Vulnerability *Glob. Environ. Change Hum. Policy Dimens.* **16** 268–81	63
CCA		
1	Smit B, Wandel J 2006 Adaptation, adaptive capacity and vulnerability *Glob. Environ. Change-Hum. Policy Dimens.* **16** 282–92	461
2	Adger W N 2006 Vulnerability *Glob. Environ. Change-Hum. Policy Dimens.* **16** 268–81	298
3	Turner B L I, *et al* 2003 A framework for vulnerability analysis in sustainability science *Proc. Natl Acad. Sci. USA* **100** 8074–9	268
4	Kelly P M and Adger W N 2000 Theory and practice in assessing vulnerability to climate change and facilitating adaptation *Clim. Change* **47** 325–52	229
5	Brooks N, Adger W N and Kelly P M 2005 The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation *Glob. Environ. Change-Hum. Policy Dimens.* **15** 151–63	197

We conducted an analysis on the thematic structure of the articles to understand the evolution of the contents within the two communities. The analysis used a machine learning set of algorithms [8, 9] that browses all the texts in the whole corpus of documents (the articles in CCA, DRR, and CCA&DRR) formed by titles, abstracts and keywords where available, and generates two multinomial probability distributions. One distribution—called *Topic* (*T*)—reproduces the frequency of each word appearing in the texts in each topic. The topic tends to cluster words with a similar meaning or that co-occur in similar thematic contexts. The second distribution is the proportion of topics in a given article, called *document topic proportion* (*DTP*). This probability distribution specifies how much of a topic is contained within any given article, so that each article is classified by a vector of *DTP* whose values are between 0 and 1. This representation allows the generation of a distance matrix of the articles with respect to their *DTP*, used to identify clusters of papers, in section 4 of the Supplementary Materials. Six time slices were adopted to investigate the evolution of the literature over time: between 1991 and 2001, 2002–2005, 2006–2008, 2009–2010, 2011–2012, 2013–2014[7].

2.2.2. Authors and collaboration networks

Besides the analysis of papers as individual entities, the bibliometric analysis also focused on authors and the networks formed by their collaborations in the 3757 papers selected (CCA, DRR, and CCA&DRR).

Authors and papers represent a bipartite network. Similarly to Biscaro and Giupponi [6] we used a script in Java to extract the authors-papers network and used a matrix multiplication to produce a collaboration (or co-authorship) network whereby a link is established between authors if they co-author a paper. Authors were identified on the basis of their first and last names[8]. This analysis allowed us to explore the structures of collaborations within and between the CCA and natural disaster communities and their evolution over time.

With respect to the authors, we explored the classification of their publications in the two research streams to assess the distribution of the authors along a continuum that spans from scholars contributing only to the CCA community, to those writing only disaster risk papers, with intermediate situations of authors with varying degrees of contribution to both. To define the contribution *R* of the author *i* to the field of CCA, we sum the number of publications by *i* appearing in the CCA dataset (CCA_i) and half of the publications also appearing in the DRR dataset ($CCA\&DRR_i$), and divide by the total number of articles written by *i* appearing in our dataset (TOT_i), as follows:

$$R_i = \left(CCA_i + CCA\&DDR_i/2\right)/TOT_i. \quad (1)$$

This contribution is computed for each time slice.

In order to detect whether the two communities are evolving into a more cohesive scientific community, we consider two structural aspects of the growing network [3, 4]. First, we relate the absolute number of single collaborations and of authors in the field to each other, and we assess how the growing number of authors is related to the dynamics of ties between them within the network. Secondly, we explore whether there is an emergence of clusters of authors linked to each other by a path. In network terms, we register the

[7] Details about the procedure for the identification of the topics are provided in section 1 of the supplementary material.

[8] Middle names were excluded, because not always reported.

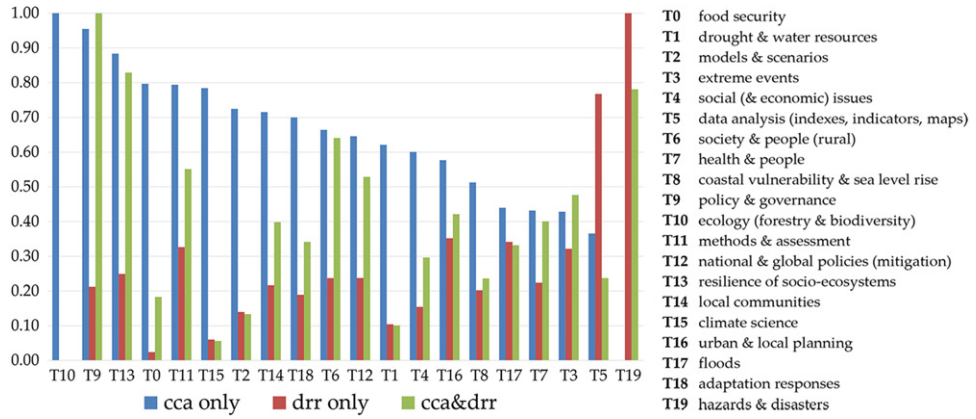

Figure 2. Topic distribution in the literature of climate change adaptation (CCA) and disaster risk (DRR).

size of the *components*, where a component is a subset of a network in which all authors are connected to each other by a path. We thus compute the *cluster susceptibility* by dividing the number of nodes in the second largest component by the number of nodes in the largest—or *giant component* [41]. We also measure the *relative size of the largest component* that is the number of authors within the giant component with respect to the number of authors in the network. Its dynamics can be considered as an indicator of the evolution of a core group of collaborating authors within the scientific community.

3. Results

3.1. Bibliometric analysis on papers and authors

3.1.1. Analysis of the content

Articles of different communities typically differ with respect to the topic-proportion. A first glance at the distribution of topics in the literature is obtained by considering the *DTP* in all articles published in the field of vulnerability until the end of 2014. Figure 2 shows the *DTP* in the 'CCA only' and 'DRR only' literatures with the blue and red bar respectively, while the green bar represents the distribution of topics in the articles that appear in both datasets. The 20 topics extracted are the main thematic contents of the whole dataset, therefore it is not surprising that the topic proportion is higher on average in the articles about adaptation, and the green line stands on average above the one of the disaster risk articles[9]. Results provide a quantitative characterization of the contents of the two literature streams, which appear to be well distinct. Each paper is characterized by a specific combination of topics (see three example in figure 3), which characterizes the contents beyond the original allocation to one of the literature streams and facilitates the identification of papers to be examined in the literature review reported in section 3.2. The CCA literature is characterized by a broader variety of topics (ecological issues, T10; policy and governance, T9; food security, T0, assessment methods, T11; resilience, T13, and climate science, T15), whereas the literature of disaster studies is highly concentrated on topic 19 (hazards and disasters) and to a minor extent on topic 5 (indicators, indexes and maps). Papers appearing in both literatures (CCA&DRR) are instead characterized by a focus on policy and governance (T9), resilience (T13) and hazards and disasters (T19)[10].

After exploring the distribution of topics within the three datasets, the interest emerged to identify possible trends over time (section 2 of supplementary materials). While the proportions of the main topics in the CCA literature show relative stability throughout the time period, the disaster risk literature instead presents a remarkable decrease of the—relative—interest in the core topic (T19) and a parallel increase of interest in data analysis methods producing vulnerability indices and maps (T5).

A dynamic evolution of the content, in section 3 of the supplementary materials, carried out through cluster analysis, shows that throughout the 25-year period two nuclei of papers persist with a clear characterization in terms of peculiar DRR (T19, in particular; recently also T5) and CCA (T8, and also T3 and T17) topics, thus sustaining the persistence of the two distinct research streams. Analyses also show that the numbers of those papers are relatively small, while the majority of publications show mixed and evolving combinations of topics. Whether this evolution could or could not be interpreted as the emergence of a new and unified field of research can be explored by analysing co-authorships, as reported in the next section.

[9] If the choice of words—the content—of the articles differs between communities, the probability that topics represent words of the 'CCA' community will be higher, because the corpus of text from which topics are extracted mainly comprises words coming from articles in the 'CCA' community.

[10] Details about the topics and the keywords characterising each cluster are provided in section 1 of the supplementary material.

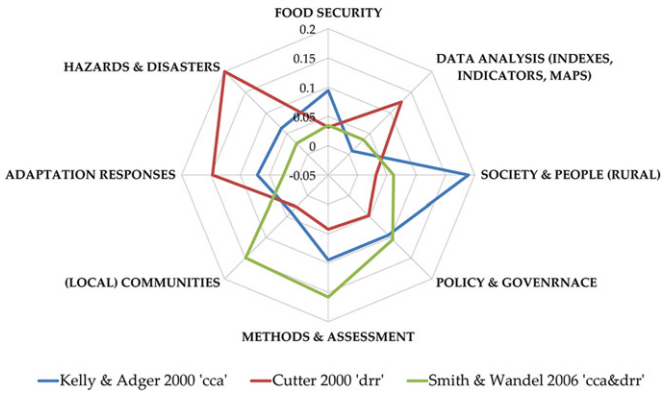

Figure 3. An example of the DTP of three papers among the most cited ones. The topics displayed are those for which the difference between the topic-proportion was at least 0.05 between the article with max and the min values.

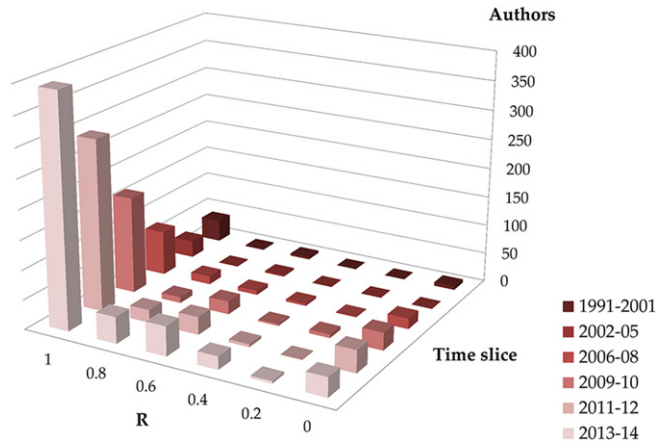

Figure 4. Authors' contributions to the 'CCA' and 'DRR' research streams. The *R* axis identifies the proportion of contribution of authors to the two streams (0 identifies authors contributing only to disaster studies, while 1 identifies those contributing only to climate change adaptation studies) and the evolution over time can be read in along the time slice axis. The higher the bar, the higher the number of authors (vertical axis).

3.1.2. Analysis of authorships and collaborations

A preliminary analysis of authorship explored whether single authors publishing more than one paper contributed to only one or both research streams, by means of the *R* index described in section 2.2.2. The higher the values, the higher the proportion of adaptation papers and vice versa, with values equal to 1 for authors publishing only CCA papers, and 0 for those publishing only on DRR. In absolute terms, authors who published more than one paper range from 50 out of 327 in the first period of time to up to 547 out of a total number of 3027 authors in the last period. Figure 4 reports the results of the analysis over time slices, and shows that while there is a proportion of around 10%–15% of authors publishing mainly papers on CCA who also publish in the disaster literature ($R = 0.6 \div 0.8$), cases of DRR authors also publishing CCA papers are rare. Over time the proportion of authors contributing to only one research stream decreases steadily from 0.88 to 0.80: a clear sign of intensifying relationships between the two communities.

The analysis of the networks of co-authorships over time shows that after 2001 there is an evident convergence of the authors towards the giant component (figure 5(A)), i.e. an emerging nucleus of authors connected to each other that can be considered as the central core of authors around whom the field structures. This can be shown by the fast descent of the cluster susceptibility (green line) after 2001. However, it is not until before the three-year period from 2006 to 2008 that a relatively large giant component is formed (red line above 20% of the authors). These three years see a large increase in the number of scientists participating in the field, the grey line, and continues to escalate in the most recent years. More quantitative information about the emergence of a unified field of science can be acquired by comparing the pace at which the number of collaborations increases to the pace at which the number of authors does. In this regard figure 5(B) shows that the number of collaborations increases at a faster pace than the number of authors, indicated by the exponent of x being greater than 1 ($r^2 = 0.9914$). Following the reasoning

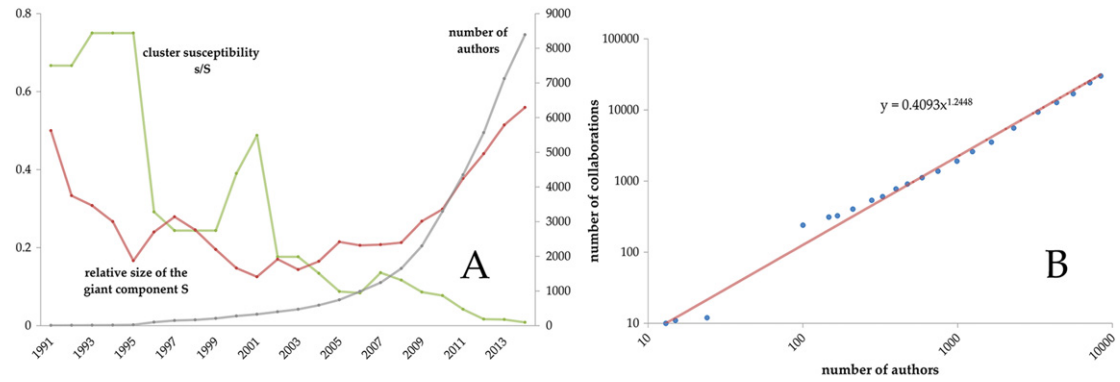

Figure 5. Structural evolution of co-authorships. (A) Trends of the giant component (red line) versus cluster susceptibility (green) demonstrating that the former grows and the latter decreases dramatically after 2007–8, with booming increase of the total number of authors. (B) Temporal evolution of number of collaborations versus number of authors, demonstrating (exponent greater than one) the increasing cohesiveness of the scientific network.

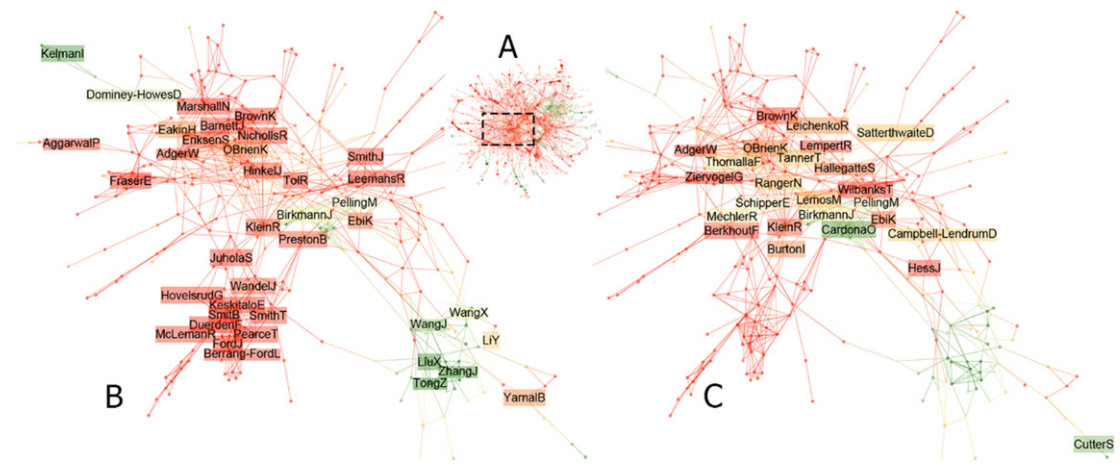

Figure 6. Network of co-authorships (CCA in red and DRR in green. Colours are coded according to the *R* index). (A) a picture of the whole network with the frame considered in B and C; (B) the selection of nodes of authors with more than four papers. Author names appear for those who published ten or more papers; (C) the same selection of nodes, but with the names of IPCC SREX authors and editors.

proposed elsewhere by Bettencourt and Kaur [4], the results of the analyses demonstrate that a consistent community with strong structured collaborations has emerged.

Two graphical representations of the author network are presented in figure 6, with nodes being the authors and the connections the co-authorship relations. Visually, authors who collaborate with each other and have many of the same co-authors tend to form 'clusters'. The core position in the plot tends to be occupied by those authors who are connected with one or more authors who have many co-authors—hubs in network terms—among whom, usually, there are other hubs. Authors less connected to hubs are visualized in the periphery of the network plot. Figure 6(A) provides a comprehensive picture of the network, while 6B and 6C report a zoom into the core of the network and selects only nodes of authors producing 4 or more papers in the 1991–2014 period (419 nodes and 947 edges extracted from the whole network with 8390 nodes and 27852 edges). Figure 5(B) shows names of authors with more than 10 publications in the whole dataset (24 years) and identifies relevant authors and their collaborations (independently from their citations). Figure 6(C) shows the same portion of the network, but with the names of authors involved in the IPCC SREX[11] and, in comparison to 5B, demonstrates that the vast majority of authors involved in the SREX belongs to a well-connected group of scholars with relatively strong previous collaborations and a quite balanced distribution of the CCA and DRR components (balanced distribution of colours). It can thus be considered a demonstration of the convergence of key authors of the two communities in a joint effort under the auspices of the IPCC.

[11] We included editors of SREX and the lead, coordinating and collaborating authors of the chapter 1; 2; 5; 7 and 8 that are related with the concept of vulnerability.

3.2. Literature review

As stated above, in accordance with several authors (see in particular [27, 34, 5, 10, 32]), this paper developed out of an initial assumption that two distinct literature streams on vulnerability exist and are relevant for climate change science: one focused on disasters and hazards (DRR or disaster risk management), and one on CCA. The results of the bibliometric analysis confirmed the validity of the initial assumption as well as revealing clear signs of increasing exchanges and convergence. Informed by those results, the review presented in this section analyses the historical evolution of the vulnerability concept starting from the disaster risk literature, which developed first, moving on to CCA papers and those across the two fields, following the historical evolution of the literature and vulnerability concepts.

The volume 'At Risk: Natural Hazards, People's Vulnerability and Disasters' with its two editions [7, 39] is by far the most cited reference in the DRR literature (see table 1). Authors define the commonplace meaning of vulnerability as the condition of 'being prone or susceptible to damage or injury'. They further develop the concept by providing a working definition as 'the characteristics of a person or group and their situation that influence their capacity to anticipate, cope with, resist and recover from the impact of a natural hazard', originated by a single or a cascade of events ([39]; p 11). The focus is on people, with the specification that the term is used to identify those that are in the worst conditions to cope with the events and impacts considered because of unfavourable combinations of social variables, such as health, age, gender, ethnicity, etc. According to this interpretation, the opposite of vulnerable should be considered being secure, thanks to people's specific capacities. Very importantly, the authors draw attention to the notion of risk, defined as a combination of vulnerability and hazard, claiming that there cannot be a disaster risk (R) if either hazards (H) or vulnerability (V) are nil, as stated in what they call a 'pseudo-equation' ([39]; p 44):

$$R = H \times V, \tag{2}$$

where V is the term which synthetizes the varying degrees of vulnerabilities of the number of people exposed—in space and time—to the specific hazard H.

Susan Cutter's seminal paper published in 1996 ([11], currently ranked fourth in terms of DRR citations according to HistCite™) provides a second fundamental reference for our review, not only for dissertations on the vulnerability concept, but also because it gives a comprehensive selection of previous definitions starting from the early 1980s. Broadly defining vulnerability as 'the potential for loss', the author acknowledges the fuzziness and divergence of existing definitions and identifies three typologies: individual, social and biophysical vulnerability. Moreover, Cutter offers a categorization of vulnerability into three themes: (i) *vulnerability as a pre-existing condition*, focused on risk/hazard exposure (very much in line with the mainstream literature on disasters); (ii) *vulnerability as a tempered response* of societal coping responses to hazards, and (iii) *vulnerability as a hazard of place*, with a focus on the spatial dimension characterizing interactions between biophysical risks and social responses. The third approach is further developed by Cutter and others in a paper ([13]; ninth most cited paper in DRR) defining vulnerability as 'the potential for loss of property or life from environmental hazards'. Moreover, a conceptual model is formalized for the *hazard-of-place* in which place vulnerability results from the spatial combination of biophysical and social vulnerabilities, both subject to a given hazard potential, deriving from the combination of the risk identified and the mitigation actions in place. Cutter and colleagues further develop their conceptual model in a subsequent paper ([12]; third most cited paper in DRR), in which they turn their attention to the social dimension—with reference to the socially created vulnerabilities to environmental hazards and the role played by inequalities—in order to determine the susceptibility of social groups in interaction with place.

The oldest seminal paper among the five most cited papers of the CCA literature is the article by Kelly and Adger (2000) on the role of vulnerability assessment for the identification of CCA responses [27]. The authors identify three main schools of thought. The first refers to the IPCC, and vulnerability is the end point of a sequence of causal relationships depending on climatic conditions, and on the sensitivity of a system and its ability to adapt. The second school of thought derives from research on food security and natural hazards, and considers vulnerability as a *focal point*, an overarching concept that, combined with the exposure to a given hazard, defines the notion of risk. The third one defines vulnerability as the *starting point* of impact analysis. The authors refer to the Latin etymology (*vulnerabilis* as the condition of the wounded soldier) to stress the point that vulnerability describes the current state of a social system resulting from its history, rather than a possible future state. Having declared that it would be foolish to search for a dominant conceptual framework, they agree with the definition of social vulnerability proposed in the volume 'At Risk: Natural Hazards, People's Vulnerability and Disasters' [7, 39] emphasizing the need to clearly identify the stresses and constraints on human capacity to respond, with an evident link to the concept of adaptation, given that adaptation is facilitated by reducing vulnerability.

A paper published by Turner and others in 2003 played a prominent role in bridging the two literatures ([35]; ranked third and sixth in HistCite™ for CCA and DRR literatures, respectively). The authors attempt to carry out a comprehensive analysis of the main

concepts related to vulnerability and to develop a conceptual framework in support of sustainability science. They point out that vulnerability emerges not only from the identification of the exposure to hazards, but also from system sensitivity and resilience. System sensitivity originates from the interactions between human and environmental conditions, while resilience results from the combination of impacts, adaptation, coping capacities and the responses in place. Vulnerability is thus 'the degree to which a system, subsystem, or system component is likely to experience harm due to exposure to a hazard, either a perturbation or stress'. In turn, perturbation is defined as a major spike in pressure beyond the usual range, while a stress is a continuous or slowly increasing pressure. Risk does not appear in the framework, but is defined as the probability and magnitude of hazard consequences. In accordance with Cutter and others [13] they emphasize the need for a local approach to the analysis of vulnerability, adopting a 'place-based' analysis that couples human-environmental systems as well as drawing upon a clear understanding of relationships with broader scales, from regional to global.

Another fundamental contribution for both literatures is provided by the paper titled 'Vulnerability' mentioned above ([1]; ranked second in CCA and fifth in DRR for citations). The focus of the paper is upon integration between vulnerability and the resilience of socio-ecological systems to enhance our understanding of the challenges caused by global social and environmental changes, system responses, and the opportunities for adaptive action. Resilience and vulnerability are two key features of socio-ecological systems (positive and negative, respectively), with the former representing their capacity to absorb shocks, re-organize and adapt, and the latter indicating their susceptibility to be harmed. In particular, Adger proposes a definition of vulnerability as 'the state of susceptibility to harm from exposure to stresses associated with environmental and social change and from the absence of capacity to adapt'. Another important contribution is the recognition that vulnerability is not easily reducible to a single quantitative metric. Instead, Adger offers a formalized and generalized measure of social vulnerability based upon relationships between vulnerability indicators and a quantification of individual well-being, accounting for the dynamic degree and severity of vulnerability and also taking into consideration reference thresholds for risk, danger or harm. Moreover, he suggests that the paradox of contrasting faces of vulnerability could be solved by accepting the two epistemological positions proposed by Karen O'Brian and colleagues: *vulnerability as an outcome* and *contextual vulnerability* (see [15, 29] for details). By supporting the distinction between two alternative, but not necessarily conflicting interpretations of vulnerability, he anticipated the latest IPCC developments considering them as additional interpretations of the notion of vulnerability, also defined as *End-point vulnerability* and *Starting-point vulnerability* ([24]; Annex II, following [29]).

O'Brian and colleagues [29] develop these concepts of outcome (or end-point) and contextual (or starting point) vulnerability in detail, linking them to two fundamentally different framings of the climate change problem: the *scientific* and the *human security framings*. Contextual vulnerability emerges from a more complex process-based and multidimensional model with interacting climatic, political, institutional, economic and social drivers of changes. The definition of *contextual vulnerability* in the IPCC AR5 Glossary refers to this paper and reads as follows: 'A present inability to cope with external pressures or changes, such as changing climate conditions. Contextual vulnerability is a characteristic of social and ecological systems generated by multiple factors and processes' ([24], p 1762). Similarly, the AR5 definition of *outcome vulnerability* refers again to O'Brian *et al* and also to Kelly and Adger [27, 30], and defines 'Vulnerability as the end point of a sequence of analyses beginning with projections of future emission trends, moving on to the development of climate scenarios, and concluding with biophysical impact studies and the identification of adaptive options. Any residual consequences that remain after adaptation has taken place define the levels of vulnerability'.

Significant contributions to the consolidation of concepts come from a series of papers aimed at developing assessment methods and models. Smit and Wandel [33] propose a model for the basic relationships of vulnerability resulting from the interactions among broad scale and local scale determinants, as a function of the exposure and sensitivity of the system to hazardous conditions and its capacity to cope, adapt and recover from their effects. In line with the IPCC approach, the link between vulnerability and adaptive capacity is stressed as two forces acting in opposite directions when the system is exposed to a specific stimulus. This paper is the most frequently cited paper in the CCA literature. Fussel and Klein [16] focus instead on a conceptual model for vulnerability assessment developed through four stages describing theory evolution over time, and categorize vulnerability models into three main streams: (i) the risk-hazard framework; (ii) the social constructivist framework, and (iii) the IPCC framework as proposed by the TAR [28]. Regarding the latter they point out that the definition of vulnerability should substitute 'or' with 'and', thus resulting in the 'degree to which a system is susceptible to, 'and' unable to cope with, the adverse effects of climate change, including climate variability and extremes'.

Another attempt to move towards a less ambiguous definition of vulnerability and a more robust assessment by means of a mathematical formalization can be found in Ionescu *et al* [21]. Ionescu and colleagues propose to specify three primitives of the resulting outcome: the vulnerable entity, the specific

stimulus and a judgement scale (worse-better). Subsequently the idea was further developed by some of the same authors together with other colleagues [40], with formalized approaches applied to the assessment of future trends (climate change studies) in the case of end-point (outcome) biophysical vulnerability, and starting point (contextual) social vulnerability applied to present conditions. Several other papers proposed operational solutions for vulnerability assessment for adaptation. Four of them focused in particular on the issue of how the various components could be aggregated in a formalized model for vulnerability assessment. Döll [14] proposed an index specific for human vulnerability to decreased groundwater availability, of interest because it proposes a combination of mathematical and logical operators, applied to groundwater recharge and three sensitivity indicators. Hinkel [19] focuses on the importance of measuring future harms, and proposes to adopt case specific solutions based on indicators. Giupponi and colleagues [17] as well as Holstein and Kropp [20] go further in the analysis of the aggregation problem by proposing dynamic models to simulate future trajectories or spatial scenarios of vulnerability as affected by climate change with case study applications.

4. Discussion and conclusions

Bibliometric analysis allowed for an initial quantitative screening of the widest set of papers (more than 3500) extracted from the WoS database. Using a combination of a computational content analysis method and analysis of scholarly networks, we highlighted a very lively research environment, with two evolving research streams that share some of the fundamental ideas, but also show remarkable differences with respect to their interests, settings and the emphasis placed on the various elements of the vulnerability concept. Bibliometric analysis showed limits for the identification of the Universe of the references, which caused the absence of important references in the bibliographic database, but it provided a very effective support to orient the review of a wide and fragmented literature. The content analysis of the traditional literature review allowed gaps to be filled, especially with respect to the seminal papers not strictly part of the two research stream examined, but related to close ones like sustainability science.

In addition to the statements about the fragmentation of the literature and the diversity of interpretations and definitions, many papers in the 1990s also remarked upon the limited efforts towards the social dimension of vulnerability, which does not appear to be fully motivated with our historical perspective. Indeed some earlier studies focused more on physical and environmental dimensions, while the socio-economic dimension has received increasing interest in recent times, but what latest developments provide are in particular efforts targeted to integrating multiple disciplinary approaches. Those works show promising and innovative developments and try to move beyond the terminological and methodological debate by proposing operational models and assessment methods. The dichotomy between environmental/ecological and social/economic systems could thus be overcome by the notion of social-ecological systems (or simply socio-ecosystems), as pointed out by the inspiring work of Adger in 2006 [1]. Moreover, a more integrated and holistic approach could facilitate further developments in which we may observe not only the convergence of the two research streams analysed herein, but also: (i) the strengthening of the exchanges with other research communities, first of all with sustainability science; and (ii) the consolidation of the glossary of related terms, first of all resilience and adaptation.

Both the literature review and the quantitative analyses confirmed the validity of the initial assumption regarding the existence of two well-identified literature streams. The two research streams both have distinct peculiar topics persisting over time, and evolving interests, as we have shown by means of the cluster analysis. The literature review and the analysis of citations demonstrate that authors in the two streams are aware of the developments in the other community. In particular, we find evidence of the propagation of approaches and concepts typical of the disaster risk literature in the CCA community since the turn of the century, as in the case of the increasing importance accorded to the notion of risk, its assessment and management in the CCA studies. Nevertheless, the proliferation of contrasting epistemologies has persisted, further complicated by the fuzziness of terms utilized for vulnerability definitions, such as exposure, sensitivity, and susceptibility.

Both communities have referent United Nations institutions: UNDRO/UNISDR for the disaster studies and the IPCC for the CCA. Our work shows that, without adequate consideration of the documents and reports produced by UN institutions it is indeed quite impossible to understand the evolution of scientific literature. Not only are their documents key references for definitions of terms (e.g. the IPCC glossaries), but they also seem to catalyse and stimulate the scientific literature with their periodic reports. For example, in the years immediately before the release of the IPCC AR4 [22], the climate change literature was flourishing and providing seminal papers, which are still on top of citations in the field.

Moreover, very recent developments within the IPCC (SREX and AR5) have made a significant contribution to reconciling contrasting definitions by offering climate change scholars a very concise definition of vulnerability that is very close to the disaster risk tradition in that it becomes one of the elements of the notion of risk. At the same time, the impossibility of proposing and adopting a single definition—

reflected in the title of this paper—is also affirmed by the inclusion of two additional definitions (outcome and contextual vulnerability). The forthcoming literature on CCA and DRR cannot avoid referring to those references for new methodological development or new terminological proposals.

Indeed, the convergence of different scientific communities and the efforts to reconcile divergent vocabularies did not appear just by chance. On the contrary, the SREX report is the result of a very concrete will for collaboration and integration, as it was proposed to the IPCC by the UNISDR and the Norwegian Government who had previously sponsored the publication of a background report co-authored by key authors of both research communities [31]. The effectiveness of the proposal was favoured by the recognized relations between natural hazards and climatic change (see e.g. the 2007 UNFCCC Bali Action Plan[12] and the 2005 UNISDR Hyogo Framework[13]) and by the mutual awareness of research conducted by the two research communities. Signs of the latter were, as we proved in this work, the wide adoption of common references and the increasing number of cross-stream co-authorship.

Our work demonstrates how international scientific institutions may function as catalysers and integrators of people and ideas. Understanding how scientific concepts—vulnerability, but also related ones, such as resilience, risk, or even sustainability—co-evolve across broader scientific disciplinary networks under the aegis of international scientific and policy institutions could be material for future research, also in view of important global initiatives recently launched, such as the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES)[14] and Future Earth[15].

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