Mapping the evolution and current trends in climate change adaptation science

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A B S T R A C T

Research on climate change adaptation has increased in number and significance since the 1970s. Yet, the volume of information on adaptation is now difficult to manage given its vast scope and spread across journals, institutions, disciplines and themes. While an increasing number of researchers have used systematic literature reviews to analyse particular themes within this rapidly growing field of research, there is still missing an overall analysis of the current state of climate change adaptation science literature and its evolution. This paper fills this gap by providing a multifaceted bibliometric review of climate change adaptation science literature that is focused on the human dimensions and how it has been constructed across time, disciplines, social relationships and geographies. Our novel review, spanning from 1978 to mid-2020, identifies the underpinning foundations of climate change adaptation literature, leading authors, countries and organisations as well as dominant research themes and priorities and explores how these have changed over time. Our results show an annual average increase of 28.5% in climate change adaptation publications, with over 26,000 authors publishing on this topic, and increasing diversity in publishing sources. Priority research topics and themes have been dynamic over time, while some core concepts (vulnerability, resilience, adaptive capacity) and sectors (water, agriculture) have remained relatively stable. The key challenge going forward is how to consolidate this vast research endeavour into a more coherent adaptation theory that in turn can better guide science of adaptation and support adaptation policy and practice (science for adaptation).

1. Introduction

Over the last two decades climate change adaptation has emerged as a central and now acknowledged component of the international climate change policy and research agenda (Klein et al., 2014; Owen, 2020; Swart et al., 2014). The Paris Agreement and its Article 7 have secured a prominent platform for climate adaptation as a key issue for global governance (Persson, 2019). Adaptation received its own ISO standard [ISO 14090] in 2019, cementing it further as a distinct area of research, policy and practice. Specific climate change adaptation conferences, such as the *Adaptation Futures* series, have been running since 2010 and new scientific degrees and professional certifications are being developed specifically for climate adaptation. That climate change adaptation literature is flourishing is evidenced also by the rapid expansion of the number of publications with a focus on climate adaptation (Di Matteo et al.,

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2018; Giupponi and Biscaro, 2015; Haunschild et al., 2016; Preston et al., 2013, 2011). In fact, thousands of climate adaptation papers are now published each year (Noble, 2019). Yet, to date, a focused analysis is still missing on the evolution of this literature, including its extent, growth and diversification over time.

Adaptation science is both basic and applied (Moss et al., 2013) and includes knowledge about the processes of adaptation and knowledge generated about adaptation" (Swart et al., 2014). This science however finds itself in a paradox: while it has quickly amassed a wealth of knowledge about the problem and potential solutions, it is "still characterized by an evolving epistemological base" (Eisenack and Stecker, 2012, p. 244). The field is plagued by "the dependent variable problem" (Biesbroek et al., 2018, p. 2) as to what counts as "adaptation" (Dupuis and Biesbroek, 2013). Large bodies of work exist that, even if not explicitly framed as climate change adaptation, still form a critical mass of knowledge that supports climate change adaptation ideas, theoretical development, and implementation (Biesbroek et al., 2018; Dupuis and Biesbroek, 2013; Keskitalo and Preston, 2019). The overall knowledge base remains fragmented (Cradock-Henry et al., 2019), including difficulties in capturing other forms of knowledge outside peer-reviewed literature such as the lived experiences in the Global South, and Indigenous knowledge in its different forms (Parsons et al., 2016). Researchers continue to opt for small case studies partly due to the now ingrained assumption about the localness of adaptation (Nalau et al., 2015; Shi et al., 2016), which makes it difficult to generalise what makes adaptation effective and in what context (Biesbroek et al., 2018; Swart et al., 2014). This in turn limits the development of a more solid adaptation theory that could provide coherence and guidance to the field (Porter et al., 2015; Schipper and Burton, 2009). Rigorous methods are lacking that document the broader causal linkages where adaptation research investments most effectively support adaptation policy (Keskitalo and Preston, 2019).

Attempting to bring order to this evolving knowledge base, authors have begun to conduct reviews on peer-reviewed adaptation literature itself. To date, these literature reviews have fallen mainly into two categories: systematic review papers on trends or factors (Berrang-Ford et al., 2019, 2011; Owen, 2020; Robinson, 2020), and specific theme reviews constructing new frameworks and guidance for methods (Berrang-Ford et al., 2015; Biesbroek et al., 2018; Dupuis and Biesbroek, 2013; Lesnikowski et al., 2019). Berrang-Ford et al. (2011) reviewed 87 papers on the implementation of climate adaptation and adaptation progress published during 2006–2009 while Robinson (2020) reviewed 208 papers on small island developing states (SIDS) covering 1990–2018 in order to document key trends pre- and post-AR5 (IPCC's 5th assessment). Owen's (2020) review of 94 articles published during 2007–2018 looked at core factors of effective climate adaptation. Method-focused reviews by Biesbroek et al. (2018) have focused on design, data and methods for adaptation policy reviews, Dupuis and Biesbroek (2013) reviewed underlying factors in conducting comparative studies on climate adaptation policies while Berrang-Ford et al. (2015) reviewed and synthesised methodologies for systematic reviews on adaptation. Lesnikowski et al. (2019) used topic modelling in adaptation governance research with UNFCCC COP (United Nations Framework Convention on Climate Change, Conference of the Parties) speeches and 25 Canadian municipalities as a methodological example of data analytics in adaptation research. Other recent review studies have looked at adaptation progress in Australia (Palutikof et al., 2019), public participation and engagement (Hügel and Davies, 2020), role of local knowledge (Klenk et al., 2017), and adaptive capacity (Siders, 2019). Others have used innovative methods to for example define generic trends across case studies such as adaptation finance archetypes that hold true across a range of local governments (Moser et al., 2019b).

While these systematic reviews provide key insights into specific trends within particular themes and methodological advancements for adaptation science, they are limited by focusing on necessarily small sample sizes, specific topics and short time horizons. Complimentary methods, such as bibliometric analysis, provide therefore a significant opportunity to discover and examine broad trends through large datasets across long time periods (Hood and Wilson, 2001; Mingers and Leydesdorff, 2015; Mongeon and Paul-Hus, 2016). This broad scale analysis is particularly important since individual scientists do not operate in an intellectual vacuum but ideas are always intertwined with the "background knowledge of the time" (Chalmers, 1982, p. 56).

Yet, to date the few papers that have attempted bibliometric reviews of climate change adaptation science literature have been too broad to provide robust explanations of the changes in research focus over time (e.g. Wang et al., 2018), not focused on climate adaptation per se (e.g. Di Matteo et al., 2018; Giupponi and Biscaro, 2015; Haunschild et al., 2016) or are now outdated (e.g. Janssen, 2007; Janssen et al., 2006). Our aim therefore is to provide a novel analysis of the main trends in peer-reviewed literature that specifically focus on the human dimensions of climate change adaptation. We demonstrate the evolution of climate adaptation science, how the research topics have changed over time, the social networks of authors via co-authorship, and the most cited papers and the foundational literature that underpins the climate adaptation science literature. This broad overview is one of the first attempts to quantify the rapid growth of climate adaptation science literature, identify the geographical and institutional sources of this knowledge, and explain the evolution of adaptation science priorities over time.

The paper is organised as follows: next, we explain the methodological choices in bibliometric analysis and the parameters that were used to search, include and exclude. Section 3 presents the results: core subject areas, journals and authors (including geographical distributions of research, scientific collaborations amongst top authors), temporal evolution of the research (including core research topics and themes), and literature foundations (including most cited journals and papers). This is followed by a discussion on what these underlying trends mean for the development of climate adaptation science and what they tell us at present how the field has and is behaving. We also reflect on the potential new areas that are likely to influence the field and discuss the intricacies of conducting large reviews given that these kinds of research methods are likely to increase in importance in the future.

2. Methods

The production of knowledge within the field of climate change adaptation has exploded since the start of the century, with increases in both specialised and transdisciplinary research (Giupponi and Biscaro, 2015; Janssen, 2007; Janssen et al., 2006; Wang et al., 2018). These factors render it near impossible to stay on top all this literature and assess the collective developments made by

this field. Thus, review methods that can assess massive and diverse sets of literature to track the rapidly evolving knowledge base are now more relevant than ever. Several literature review techniques exist such as narrative reviews (e.g. Baumeister and Leary, 1997; Wong et al., 2013), systematic reviews, and *meta*-analyses (e.g. Davis et al., 2014; Liberati et al., 2009; Moher et al., 2014) as well as bibliometric, visualisation and content analysis reviews (Mingers and Leydesdorff, 2015; Vinkler, 2010). While narrative, systematic and *meta*-analyses are well-established and explored review methods in this field, they are constrained by their ability to assess relatively small bodies of literature (e.g. less than 500 publications), whereas bibliometrics use statistical analysis of publication metadata and thus, can assess much larger literature sets (van Eck and Waltman, 2010). The current study employs a combination of bibliometric, visualisation and content analysis techniques to analyse the climate change adaptation science literature.

And still, capturing all relevant publications related to a specific field is difficult (Buckland and Gey, 1994), especially with a rapidly developing, comprehensive and transdisciplinary research field like climate change adaptation. Historically, this field has been conceptualised under several collective phrases as it has evolved (Wang et al., 2018). Thus, determining an appropriate query requires a systematic approach, such as iterative query reformulation (Wacholder, 2011) where analysis of preliminary search results of key papers inform renewed searches (Wang et al., 2014). This study implemented a similar query formulation method to search for climate change adaptation literature in the well-regarded, international databases Scopus and Web of Science Core Collection (Fig. 1), where these databases were selected to prevent geographic biases and increase publication coverage (Falagas et al., 2008).

However, initial search results returned numerous publications concerning biological adaptation to climate change, as terminology
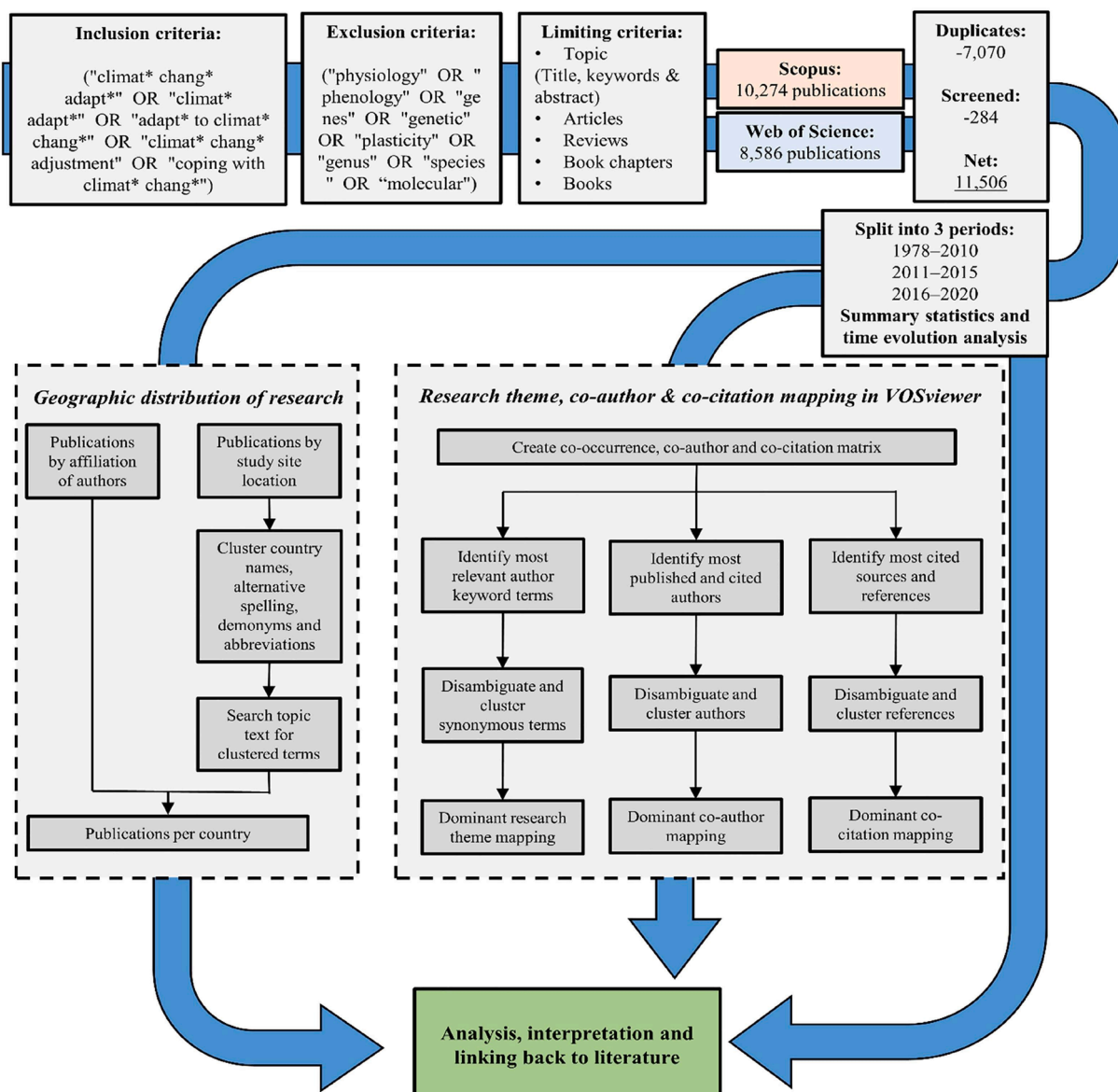

Fig. 1. Multifaceted bibliometric analysis framework.

is shared between these research fields. Therefore, irrelevant publications that lacked a societal dimension where iteratively filtered out by adding exclusion terms to the query. This process included successively adding exclusion terms (e.g. physiology, phenology, genes, genetic, plasticity, genus, species or molecular), which were determined using iterative query reformulation (Wacholder, 2011) and do not reflect the human dimensions of climate change adaptation. Search results were then limited to articles, reviews, book chapters and books in addition to limiting to 'topic section' (title, keywords and abstracts) to identify publications primarily focusing on climate change adaptation. While this may not identify all relevant publications, it selects the publications where authors have

Table 1

Overview of publications on climate change adaptation from Web of Science and Scopus split into three time periods: early (1978–2010), emerging (2011–2015) and latest (2016–2020).

Categories	1978–2010		2011–2015		2016–2020		Total	
	N	%	N	%	N	%	N	%
Publications	1,188	10.3	4,035	35.1	6,283	54.6	11,506	100.0
Type of publication								
Articles	1,007	84.8	3,098	76.8	5,224	83.1	9,329	81.1
Book chapters	67	5.6	585	14.5	583	9.3	1,235	10.7
Reviews	84	7.1	236	5.8	422	6.7	742	6.4
Books	29	2.4	115	2.9	55	0.9	199	1.7
Language								
English	1,117	94.0	3,863	95.7	6,058	96.4	11,038	95.9
Chinese	9	0.8	26	0.6	61	1.0	96	0.8
German	15	1.3	56	1.4	24	0.4	95	0.8
French	17	1.4	44	1.1	24	0.4	85	0.7
Spanish	5	0.4	17	0.4	62	1.0	84	0.7
Subject areas								
Environmental Sciences	325	27.4	1,075	26.6	1,950	31.0	3,350	29.1
Environmental Studies	281	23.7	981	24.3	1,635	26.0	2,897	25.2
Meteorology & Atmospheric Sciences	131	11.0	431	10.7	753	12.0	1,315	11.4
Water Resources	95	8.0	429	10.6	599	9.5	1,123	9.8
Green & Sustainable Science & Technology	23	1.9	128	3.2	538	8.6	689	6.0
Journals								
Climatic Change	53	4.5	110	2.7	150	2.4	313	2.7
Sustainability	1	0.1	30	0.7	204	3.2	235	2.0
Climate & Development	19	1.6	72	1.8	140	2.2	231	2.0
Environmental Science & Policy	22	1.9	59	1.5	147	2.3	228	2.0
Regional Environmental Change	1	0.1	93	2.3	127	2.0	221	1.9
Country								
United States	272	22.9	931	23.1	1,538	24.5	2,741	23.8
United Kingdom	201	16.9	535	13.3	795	12.7	1,531	13.3
Australia	93	7.8	579	14.3	722	11.5	1,394	12.1
Germany	78	6.6	391	9.7	574	9.1	1,043	9.1
Canada	109	9.2	287	7.1	431	6.9	827	7.2
Organisations								
Wageningen University	11	0.9	84	2.1	128	2.0	223	1.9
Chinese Academy of Science	7	0.6	66	1.6	123	2.0	196	1.7
CSIRO	8	0.7	96	2.4	90	1.4	194	1.7
Griffith University	6	0.5	60	1.5	93	1.5	159	1.4
Australian National University	10	0.8	54	1.3	57	0.9	121	1.1
Most published authors								
Ford, J.D.	4	0.3	26	0.6	34	0.5	64	0.6
Klein, R.J.T.	14	1.2	17	0.4	11	0.2	42	0.4
Juhola, S.	2	0.2	15	0.4	21	0.3	38	0.3
Biesbroek, R.	2	0.2	9	0.2	26	0.4	37	0.3
Wamsler, C.			10	0.2	25	0.4	35	0.3
Number of authors								
Total authors	3,254		13,724		24,496		41,474	
Total unique authors	2,578		9,942		17,848		26,808	
Authors with only one publication	2,215	85.9	7,969	80.2	14,230	79.7	20,391	76.1
Authors per publication	2.7		3.4		3.9		3.6	
Most cited authors								
Adger, W.N.	5,540	9.3	136	0.2	75	0.2	5,751	3.3
Tompkins, E.L.	2,188	3.7	521	0.6	13	0.0	2,722	1.6
Mastrandrea, M.D.	1,424	2.4	1,238	1.5			2,662	1.5
Ford, J.D.	638	1.1	1,493	1.8	463	1.4	2,594	1.5
Ebi, K.L.	449	0.8	1,369	1.7	771	2.4	2,589	1.5
Citations								
Total	59,804	34.2	82,871	47.4	32,279	18.4	174,954	100.0
Highest cited publication	1341		1217		457		1341	
Average	50.3		20.6		5.1		15.2	

N denotes number of publications unless referring to number of citations.

prioritised climate change adaptation as a core focus of their publication. Thus, bibliometric metadata were retrieved from the Scopus and Web of Science database on 16 June 2020 (Fig. 1).

Scopus returned 10,274 publications while there were 8,586 publications extracted from Web of Science Core Collection. Publication metadata from these two sources were compiled into a database and duplicates were removed ($N = 7,070$). Although the query used in this study included exclusion terms to filter those publications that concerned biological adaptation to climate change, a further 284 publications were removed from the database after careful review of abstracts, keywords and titles by both authors. The final database contained 11,506 publications, where metadata were manipulated to identify temporal patterns in the literature including splitting into three broad time periods (early research 1978–2010, emerging research 2011–2015 and the latest research 2016–2020) as well as on an annual basis. The parameters of these time periods were selected based on temporal distribution of publications, ensuring there was enough data within each period to make sound comparisons (Verrall and Pickering, 2020), and to highlight the rapid expansion of publications after 2010.

The number of publications were not normalised by population given that the number of researchers within a population is unlikely to explain why some countries fare better in adaptation science than others. Main authors, organisations, journals, subject areas (Web of Science Core Collection Categories) and spatial trends in the research were assessed. Since subject areas differ between Scopus and Web of Science, we coded publications from Scopus to the Web of Science Core Collection Categories based on abstracts, titles and keywords (Verrall and Pickering, 2020). Publications assigned to countries for spatial analysis were calculated in two ways: (a) by author affiliation and (b) by content analysis of 'topic sections' to determine where research was focused. Determining where the research was focused was calculated by analysing the abstracts for the frequency of occurrences for each country to provide a relative measure of research density (Verrall and Pickering, 2020). All contributing authors and subject areas are included, so some publications may be counted multiple times (Haunschild et al., 2016; Mingers and Leydesdorff, 2015).

To identify dominant research topics and themes as well as co-author and co-citation interconnections, the bibliometric analysis package VOSviewer (van Eck and Waltman, 2010) was used to visualise and map the literature (see www.vosviewer.com). To reduce ambiguity, keywords, authors and reference titles were clustered using thesauri prior to analysis (Waltman et al., 2010). The distance-based maps produced here are generated by bibliographic coupling as a method to position nodes (e.g. keywords, authors, reference titles) and are weighted by number of documents/citations and link strength (Waltman et al., 2010). The distance between nodes is relative to the bibliographic similarity and nodes are allocated clusters which identify closely interrelated nodes. VOSviewer uses a modularity-based clustering method, which is comparable to multidimensional scaling and is generated by the smart local moving algorithm (Waltman and Van Eck, 2013; Waltman et al., 2010).

3. Results

3.1. Core subject areas, journals and authors

As of June 2020, there were 11,506 publications that are primarily focused on climate change adaptation based on the terms used by authors in titles, abstracts and keywords (Table 1). The literature consists mainly of articles ($N = 9,329$; 81.1%) but includes book chapters ($N = 1,235$; 10.7%), reviews ($N = 742$; 6.4%) and books ($N = 199$; 1.7%). The research was published in 26 languages with most publications in English ($N = 11,038$; 95.9%), but some in Chinese ($N = 96$; 0.8%) and German ($N = 95$; 0.8%). Based on the Web of Science categories, the main subject areas were 'environmental sciences' ($N = 3,350$; 29.1%), 'environmental studies' ($N = 2,897$; 25.2%), 'meteorology and atmospheric sciences' ($N = 1,315$; 11.4%) and 'water resources' ($N = 1,123$; 9.8%) while there was less research concerning 'green and sustainable science and technology' ($N = 689$; 6.0%).

Researchers in the United States authored many publications ($N = 2,741$; 23.8%), followed by researchers from the United Kingdom ($N = 1,531$; 13.3%), Australia ($N = 1,394$; 12.1%), Germany ($N = 1,043$; 9.1%) and Canada ($N = 827$; 7.2%) (Table 1). Beyond these five countries, research on climate change adaptation has been published by an additional 169 countries, with 21 of those countries contributing over 100 publications (Fig. 2a). For those studies that focus on a particular country, most of the research focuses on the United States ($N = 1,181$; 12.9%) followed by Australia ($N = 622$; 6.8%); China ($N = 586$; 6.4%), India ($N = 482$; 5.3%) and Canada ($N = 383$; 4.2%) (Fig. 2b). Overall, countries from Africa and southern Asia seem to receive relatively high research focus in comparison to research output. Furthermore, there are more countries that have received research focus (197 countries) compared to countries which have published research (173 countries).

The journals that have contributed the most to this literature include Climatic Change ($N = 313$; 2.7%), Sustainability ($N = 235$; 2.0%), Climate and Development ($N = 231$; 2.0%), Environmental Science and Policy ($N = 228$; 2.0%) and Regional Environmental Change ($N = 221$; 1.9%), (Table 1). The leading organisations that contributed to this literature were Wageningen University ($N = 233$; 1.9%) followed by the Chinese Academy of Sciences ($N = 196$; 1.7%), CSIRO (The Commonwealth Scientific and Industrial Research Organisation) ($N = 194$; 1.7%), Griffith University ($N = 159$; 1.4%) and Australian National University ($N = 121$; 1.1%). The most published authors of this literature were J.D. Ford ($N = 64$; 0.6%), R.J.T. Klein ($N = 42$; 0.4%) and S. Juhola ($N = 38$; 0.3%). However, most authors ($N = 20,391$; 76.1%) were not specialists on the topic, having only authored one publication. The most cited authors within this literature were W.N. Adger ($N = 5,751$; 3.3%), E.L. Tompkins ($N = 2,722$; 1.6%) and M.D. Mastrandrea ($N = 2,662$; 1.5%).

When analysing co-authorship links among leading authors with at least 10 publications and 500 citations, several distinct collaborative clusters emerged (Fig. 3). Co-authorships show clear patterns of relatively tight collaboration relationships but also lack of cross-cluster collaboration: for example, J.D. Ford collaborates mostly with L. Berrang-Ford, R. Biesbroek and B. Smit whereas in another grouping W.N. Adger, J. Barnett, S. Dessai, C. Conway, A. Wreford, J. Wolf and B.L. Preston write together. Here, minimum line strength is based on one co-authored publication. The strong linkages between authors show that within cluster collaboration is

a)

b)
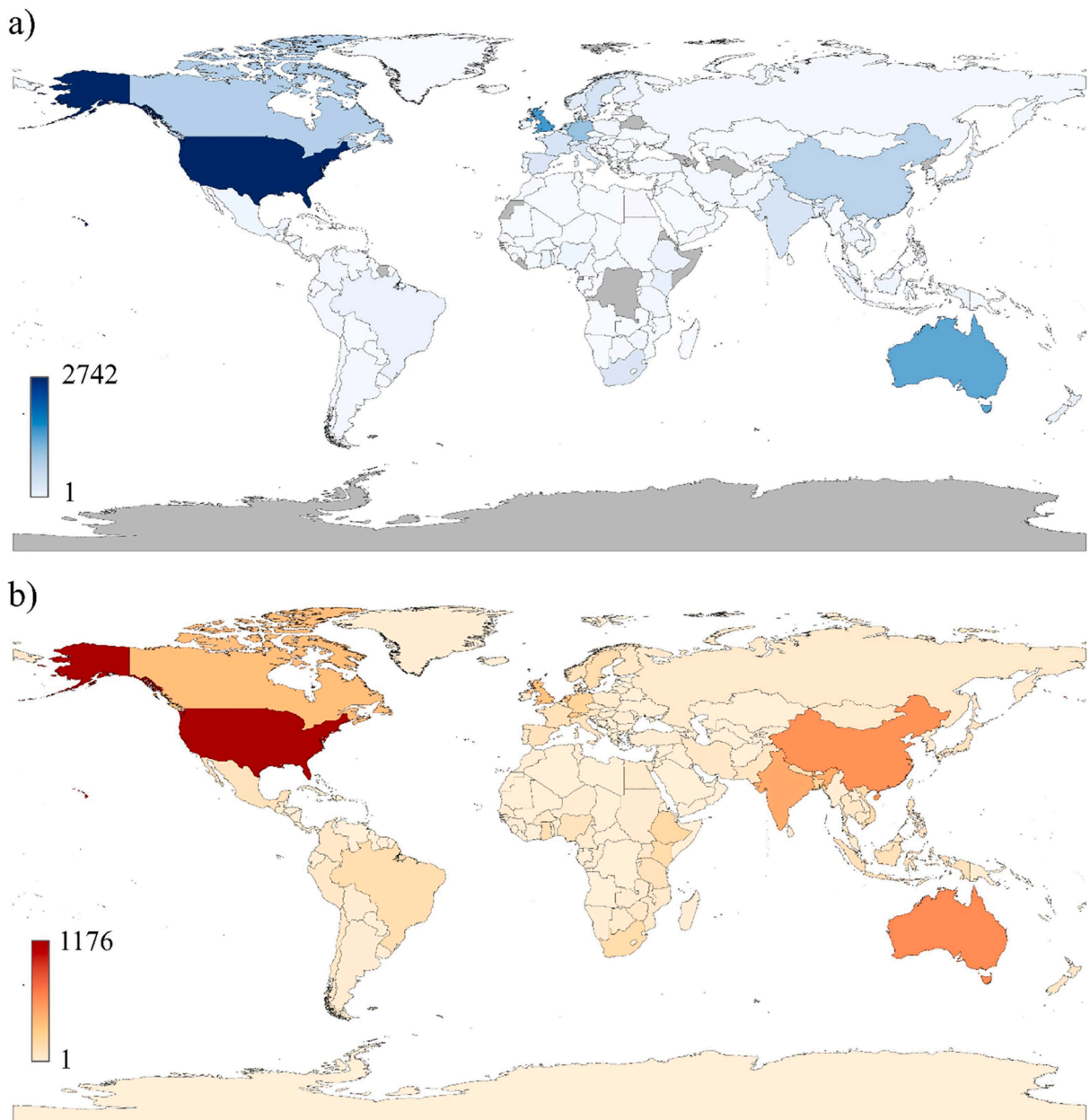
Fig. 2. Global distribution of publications by a) affiliation of authors and b) the country where the focus of the research was based. Titles, keywords and abstracts were searched for all mentions of countries to identify which countries were the focus of the research. All contributing authors are included, so some publications may be counted multiple times.

strong while cross-collaboration among top authors is rare. However, there are a few leading authors who have collaborated broadly with others on highly cited publications including R.J.T. Klein (19 links), W.N. Adger (15 links) and F.G.H. Berkhout (15 links).

3.2. Temporal evolution of the research

The first recorded publication from this literature was published in 1978 and assessed the relationship between climatic variations and horticultural trade flows in Europe (Folley, 1978). There were only 1,188 publications (10.3%) over the next 32 years (1978–2010), after which there has been a rapid increase in research on this topic with 4,035 publications (35.1%) over the following five years in the emerging period (2010–2015) and a further 6,283 publications (54.6%) in the latest five years (Table 1). The greatest increase in publications on this topic occurred between the five-year period of 2006–2010 (540% increase from previous five years). Overall, this literature has seen an average annual growth rate of 28.5% and is thus set to double in size by early 2022.
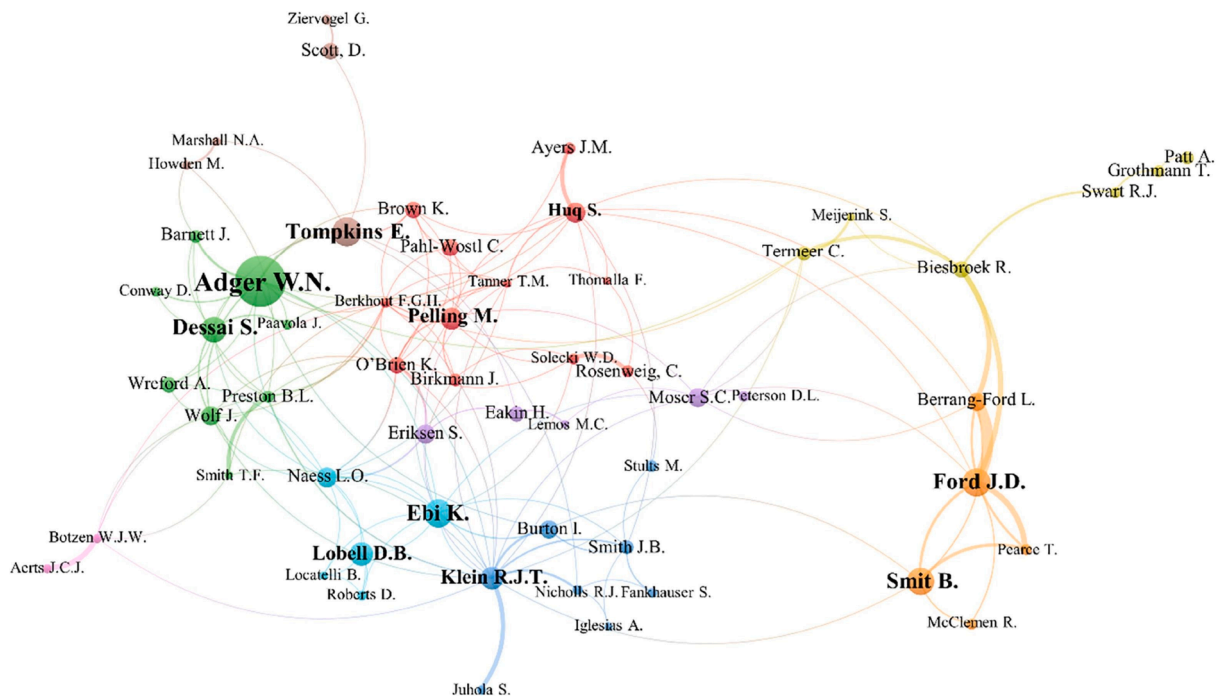
Fig. 3. Co-authorship of leading authors with at least 10 publications and 500 citations (60 authors) with the data displayed as distance maps, using VOSviewer software (van Eck and Waltman, 2019). Lines are weighted by the number of links, with minimum line strength indicating one co-authored publication. Circles are weighted by the number of citations and top ten cited authors denoted by bold labels.

The diversity of subject areas covered by this literature has expanded considerably through time (Fig. 4a). The first publications from this literature focused on 'economics', 'meteorology and atmospheric sciences' and 'multidisciplinary agriculture' but 'environmental sciences' and 'environmental studies' have become the dominant subject areas through time. Both 'multidisciplinary agriculture' and 'economics' were key subject areas until 1995, after which research on 'water resources' increased considerably. Research focus began to diversify from natural sciences to better encompass human dimensions such as 'regional and urban planning', 'development studies' and 'geography' from 2005 onwards, and most recently, 'green and sustainable science and technology' has become a key research area.

Considering the temporal publication dynamics of countries, the United States and the United Kingdom have led this literature since its inception while Canada was also an important early contributor (Fig. 4b). Since 2010, Australia has emerged as a research powerhouse, with Germany also considerably increasing its research output. The research of these leading countries has been excelled by a handful of research organisations (Fig. 4c), with several organisations from Australia (CSIRO, Griffith University, Australian National University), the United Kingdom (University of Oxford, University of Leeds and University of London) and the Netherlands (Wageningen University and University of Utrecht). University of London and University of Oxford were leading contributions to this literature before 2010, but more recently, Wageningen University, CSIRO, the Chinese Academy of Science and Griffith University have emerged as the core organisations publishing on this topic.

The leading journals that have published this literature have also evolved over time (Fig. 4d). Early work on climate change adaptation was naturally published in those journals that were forerunners in this area: *Climatic Change* (established 1978), *Global Environmental Change* (established 1990) and *Mitigation and Adaptation Strategies for Global Change* (established 1996). *Regional Environmental Change* (established 1999) has risen rapidly as a major publication outlet for climate adaptation since 2010. From 2004 onwards, journals such as *Environmental Science and Policy* (established 2001) have also increased their publication outputs on climate adaptation. After 2005, several newer journals began rapidly publishing on this topic including *Sustainability* (established 2009), *International Journal of Climate Change Strategies and Management* (established 2008) and *Science of the Total Environment* (established 2014). The overall strongest journal in this field remains *Climatic Change*.

3.3. Core research topics and themes

The most cited publications of this literature cover topics such as food security (Lobell et al., 2008; Pittelkow et al., 2015; Rosenzweig et al., 2013; Smit and Skinner, 2002), adaptive capacity (Adger et al., 2005, 2003; Bryan et al., 2009; Füssel, 2007; Grothmann and Patt, 2005; Kates et al., 2012; Pahl-Wostl, 2009; Pelling, 2010; Smit et al., 2000; Wilby and Dessai, 2010), health impacts (Costello et al., 2009), climatic extremes (Dore, 2005; Field et al., 2012; Littell et al., 2009; Taylor et al., 2013), social capital (Adger, 2003; Pelling and High, 2005), and limits (Adger et al., 2009; Riahi et al., 2017) and barriers (Moser and Ekstrom, 2010) to adaptation (S3
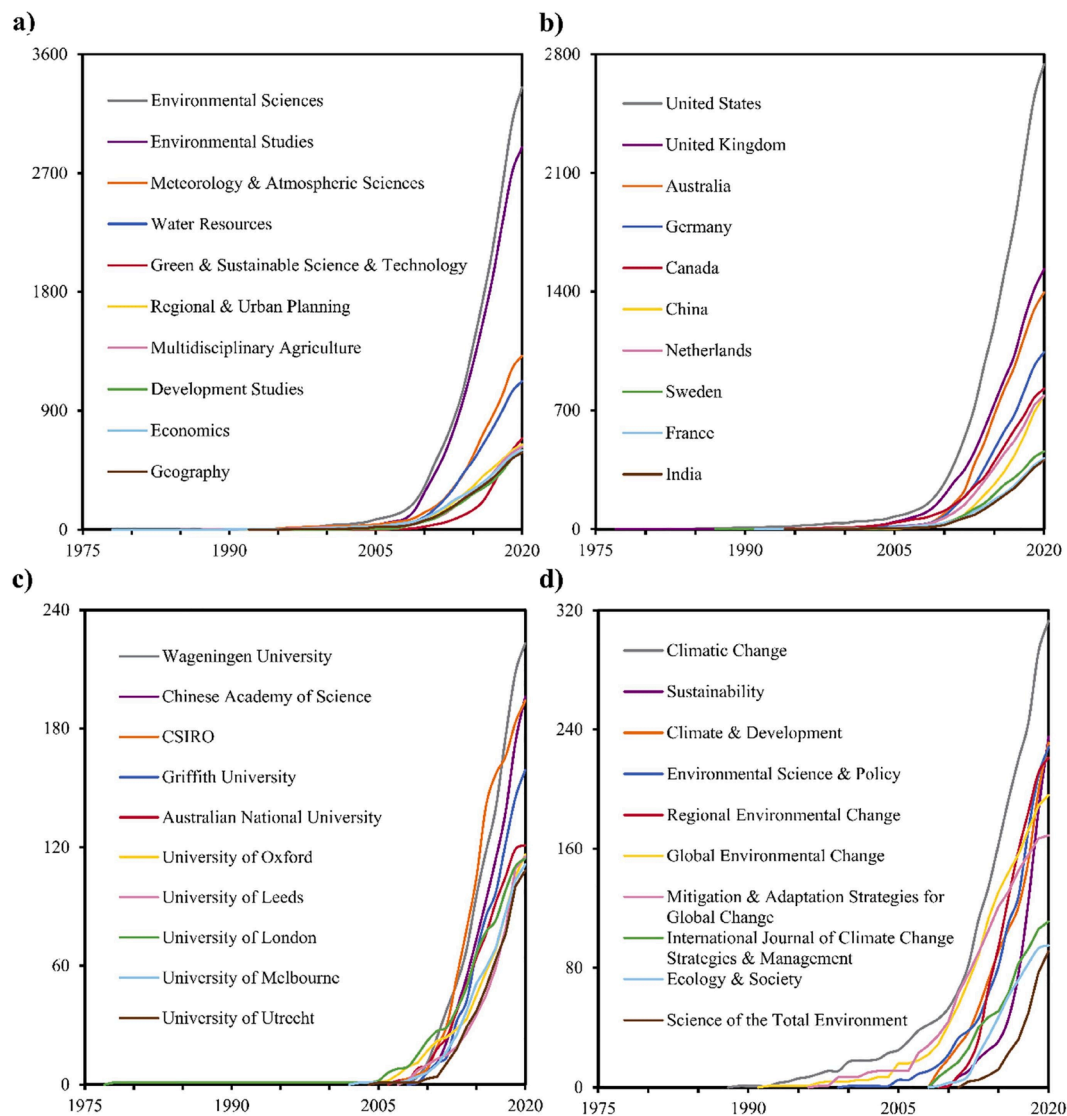
Fig. 4. Temporal trends (1978–2020) of cumulative number of publications by leading subject areas (a), countries based on author affiliation (b), organisations (c), and journals (d). All assigned subject areas and contributing authors are included, so some publications may be counted multiple times. Data from 2020 is incomplete as it was collected on June 16. Subject area categories are based on Web of Science Core Collection Categories (https://bit.ly/2XnCKk9).

Table).

3.4. What have been the priority research themes?

Keywords chosen by authors highlight the core focus of publications and denote research topics. After clustering synonymous author keywords across this literature and general terms used to search for the literature such as 'climate change and 'climate change adaptation were excluded (S2 Table) 15 534 unique author keywords were present. Over the period 1978–2020 the most common research topics were *vulnerability* ($N = 539; 4.7\%$) *resilience* ($N = 528; 4.6\%$) *agriculture* ($N = 329; 2.9\%$) *adaptive capacity* ($N = 326; 2.8\%$) and *mitigation*[2] ($N = 312; 2.7\%$) (S4 Table). Much less research focus has been over time on for example *community-based adaptation* (75th) *transformation* (90th) and *capacity building* (99th) (S4 Table). More generally five predominant themes became apparent when common co-occurring keywords were mapped (Fig. 5)

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[2] Mitigation can be both interpreted as greenhouse gas reductions or mitigating harm. The methodology here is not designed to distinguish the direct context in which this keyword is used.

Theme 1, and much of the literature, is centred around the concept of *vulnerability* to climate change (Adger, 2006; Cannon and Müller-Mahn, 2010), which is often researched in conjunction with *resilience* to climate change (Béné et al., 2014; Tyler and Moench, 2012) and how this relates to *natural hazards* such as *flooding* (Adger, 2003; Harries and Penning-Rowsell, 2011; Lo, 2013; Næss et al., 2005). Furthermore, a considerable amount of *resilience* research focuses on *disaster risk reduction* (Birkmann and von Teichman, 2010; Thomalla et al., 2006; van Aalst et al., 2008). S*mall island developing states* (SIDS) (Kuruppu and Liverman, 2011; Mercer, 2010; Tompkins, 2005) and *developing countries* (Eriksen and O'Brien, 2007; Mertz et al., 2009; O'Brien et al., 2008) are often the focus of research because of their pronounced *vulnerability* to climate change.

Research in Theme 2 assesses *risks* (Ford and Smit, 2004; Scheraga and Grambsch, 1999)*, risk management* (Birkmann and von Teichman, 2010; Field et al., 2012) and *decision making* (Adger et al., 2005; Dittrich et al., 2016), and how *uncertainty* factors into these processes (Gober and Kirkwood, 2010; Kundzewicz et al., 2017). Other key aspects of this cluster include *risk perceptions* and the *communication* of risks (Carlton and Jacobson, 2013; Taylor et al., 2014), as well as *adaptive management* (Hansen et al., 2010; Seidl and Lexer, 2013) and *extreme weather* (Hulme, 2014; Mirza, 2003).

Theme 3 is centred around climate change adaptation in *agriculture* (McCord et al., 2015; Nicholas and Durham, 2012; Westerhoff and Smit, 2009), the *impacts* of climate change (Ciscar et al., 2011; Mertz et al., 2009; Smit et al., 2000) as well as *strategies* to adapt to
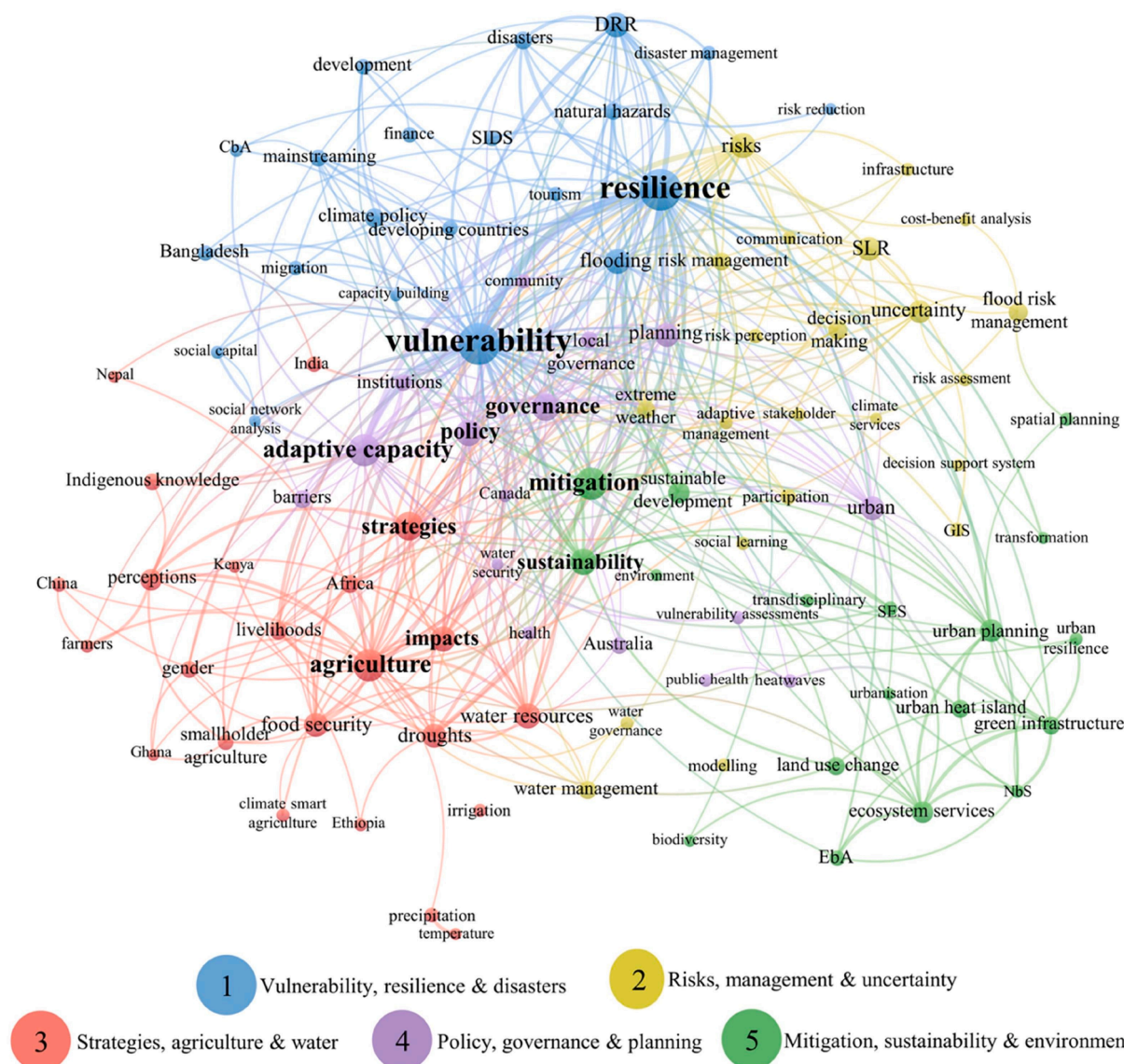
Fig. 5. Five major themes in the literature based on the 100 most commonly used author keywords (see Table S4). The terms 'climate change' and 'climate change adaptation' were excluded as these were major key words that were used to look for the literature. The size of the circle is proportional to the occurrence of the keyword, while links represent keywords used together in at least three publications with the line thickness proportional to the strength of co-occurrence. Minimum line strength links keywords that co-occur in five or more publications.

a)   **1978–2010**

b)   **2011–2015**

c)   **2016–2020**

(caption on next page)
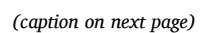
Fig. 6. Major themes in the literature based on the 50 most commonly used author keywords (see Table S4) for each of the three time periods: a) early (1978–2010), b) emerging (2011–2015) and latest (2016–2020). The terms 'climate change' and 'climate change adaptation' were excluded as these were major key words that were used to look for the literature. The size of the circle is proportional to the occurrence of the keyword, while links represent keywords used together in at least three publications with the line thickness proportional to the strength of co-occurrence. Minimum line strength links keywords that co-occur in five or more publications.

climate change (Biesbroek et al., 2010; Davoudi et al., 2013; Few et al., 2007). Research concerning a*griculture* has been widely conducted in developed regions such as North America (Arbuckle et al., 2015; Kaufmann and Snell, 1997; Southworth et al., 2000) but also in developing regions of Africa (Biazin et al., 2012; Kabubo-Mariara and Karanja, 2007; Milder et al., 2014) and south Asia (Islam and Nursey-Bray, 2017; Mishra et al., 2013; Tripathi and Mishra, 2017). In developing regions, there is often an emphasis on the impacts on *smallholder agriculture* (Gandure et al., 2013; Mapfumo et al., 2013; Wood et al., 2014). There has also been considerable focus on *agriculture* and the *perceptions* of farmers (Bryan et al., 2009; Le Dang et al., 2014; Yaro, 2013), as well as *food security* (Di Falco et al., 2011; Rosenzweig et al., 2013; Shiferaw et al., 2011) as climate changes, resulting in more severe and frequent *droughts* (Conway

Table 2

The 50 most frequently used author keywords for early research (1978–2010), emerging research (2011–2015) and latest research (2016–2020).

	Keywords								
	1978–2010	N	%	2011–2015	N	%	2016–2020	N	%
1	vulnerability	64	5.4	vulnerability	209	5.2	resilience	344	5.5
2	mitigation	47	4.0	resilience	150	3.7	vulnerability	266	4.2
3	adaptive capacity	39	3.3	adaptive capacity	135	3.3	agriculture	197	3.1
4	resilience	34	2.9	agriculture	109	2.7	mitigation	164	2.6
5	impacts	27	2.3	mitigation	101	2.5	strategies	163	2.6
6	agriculture	23	1.9	strategies	88	2.2	adaptive capacity	152	2.4
7	policy	19	1.6	governance	87	2.2	sustainability	127	2.0
8	drought	18	1.5	policy	81	2.0	governance	123	2.0
9	governance	18	1.5	impacts	78	1.9	(DRR) disaster risk reduction	121	1.9
10	risks	17	1.4	water resources	74	1.8	policy	117	1.9
11	sustainable development	17	1.4	flooding	69	1.7	urban	117	1.9
12	water resources	17	1.4	risks	67	1.7	flooding	107	1.7
13	SLR (sea level rise)	16	1.3	sustainability	65	1.6	water resources	107	1.7
14	flooding	16	1.3	planning	63	1.6	SLR (sea level rise)	106	1.7
15	risk management	16	1.3	food security	63	1.6	drought	105	1.7
16	climate policy	16	1.3	(DRR) disaster risk reduction	63	1.6	risks	104	1.7
17	developing countries	15	1.3	urban	61	1.5	food security	104	1.7
18	sustainability	15	1.3	drought	60	1.5	planning	102	1.6
19	uncertainty	14	1.2	urban planning	60	1.5	ecosystem services	99	1.6
20	planning	13	1.1	uncertainty	60	1.5	sustainable development	98	1.6
21	development	13	1.1	perceptions	56	1.4	impacts	96	1.5
22	strategies	12	1.0	SLR (sea level rise)	53	1.3	urban planning	89	1.4
23	Africa	11	0.9	disasters	41	1.0	perceptions	82	1.3
24	Norway	10	0.8	mainstreaming	41	1.0	uncertainty	80	1.3
25	water management	10	0.8	climate policy	41	1.0	green infrastructure	78	1.2
26	natural hazards	10	0.8	ecosystem services	40	1.0	decision making	74	1.2
27	institutions	10	0.8	institutions	40	1.0	urban heat island	73	1.2
28	livelihoods	10	0.8	barriers	40	1.0	flood risk management	73	1.2
29	Canada	9	0.8	decision making	39	1.0	extreme weather	72	1.1
30	adaptive management	9	0.8	local governance	38	0.9	gender	67	1.1
31	food security	9	0.8	land use change	37	0.9	land use change	66	1.1
32	health	9	0.8	sustainable development	37	0.9	water management	63	1.0
33	disasters	9	0.8	flood risk management	36	0.9	SIDS (small island developing states)	63	1.0
34	mainstreaming	9	0.8	Africa	35	0.9	Africa	61	1.0
35	insurance	9	0.8	risk management	35	0.9	barriers	61	1.0
36	(DRR) disaster risk reduction	9	0.8	water management	35	0.9	livelihoods	60	1.0
37	community	8	0.7	Australia	35	0.9	NbS (Nature-based Solutions)	57	0.9
38	extreme weather	8	0.7	Indigenous knowledge	32	0.8	smallholder agriculture	57	0.9
39	tourism	8	0.7	modelling	30	0.7	disasters	54	0.9
40	Australia	8	0.7	disaster management	29	0.7	EbA (Ecosystem-based Adaptation)	54	0.9
41	local governance	8	0.7	extreme weather	29	0.7	climate policy	54	0.9
42	decision making	8	0.7	developing countries	29	0.7	Indigenous knowledge	52	0.8
43	environment	8	0.7	Bangladesh	29	0.7	climate-smart agriculture	51	0.8
44	capacity building	7	0.6	natural hazards	27	0.7	risk management	50	0.8
45	modelling	7	0.6	development	27	0.7	Bangladesh	50	0.8
46	water security	7	0.6	urban heat island	27	0.7	SES (socio-ecological systems)	49	0.8
47	social learning	7	0.6	spatial planning	27	0.7	natural hazards	48	0.8
48	migration	7	0.6	livelihoods	26	0.6	participation	48	0.8
49	SIDS (small island developing states)	6	0.5	migration	26	0.6	urban resilience	47	0.7
50	social capital	6	0.5	Canada	26	0.6	finance	47	0.7

and Schipper, 2011; Huntjens et al., 2012; Simelton et al., 2013) and a need to assess the use of *water resources* (Biazin et al., 2012; Jägermeyr et al., 2016; Rasul and Sharma, 2016).

Theme 4 encompasses research on *policy* (Adger et al., 2003; Dessai and Hulme, 2004; Smit and Skinner, 2002), *governance* (Birkmann et al., 2010; Burch, 2010; Eriksen and O'Brien, 2007) and aspects of *planning* (Measham et al., 2011; Preston et al., 2011; Wheeler, 2008). The role of *governance* in climate change adaptation has focused mostly on *institutions* (Hurlimann et al., 2014; Juhola and Westerhoff, 2011; Vink et al., 2013). Assessing the *adaptive capacity* of society to climate change has received considerable attention (Grothmann and Patt, 2005; Pahl-Wostl, 2009; Pelling and High, 2005), particularly in *urban* areas (Ren et al., 2011; Tyler and Moench, 2012; Wilhelmi and Hayden, 2010).

Research focusing on *mitigation* (Revi, 2008; Tol, 2005; Tompkins and Neil Adger, 2005) and *sustainability* (Adger et al., 2005; Ellison et al., 2017; Tan et al., 2011) were the central topics of theme 5, and largely focused on how *urban planning* (Birkmann et al., 2010; Maimaitiyiming et al., 2014; Wardekker et al., 2010) and *sustainable development* (Eakin et al., 2014; Eriksen et al., 2011; Mirza, 2003) can alleviate the impacts of climate change. There has also been considerable focus on *ecosystem services* (Capon et al., 2013; Ellison et al., 2012; McPhearson et al., 2015), which are strongly linked to conserving *biodiversity* (Essl et al., 2012; Morecroft et al., 2012; Pittock et al., 2008), and how these services may be maintained in a changing climate through *ecosystem-based adaptation* (Brink et al., 2016; Roberts et al., 2012; Vignola et al., 2009), *nature-based solutions* (Derkzen et al., 2017; Faivre et al., 2017; Kabisch et al., 2016) and *green infrastructure* (Gill et al., 2008; Matthews et al., 2015; Norton et al., 2015).

3.5. How have priority topics changed over time?

Drilling down to specific periods show in detail how some topics have fluctuated over time with upward, downward and stable trends (Fig. 6). Generally, research has diversified with the increased volume of publications through time. Research concerning *vulnerability*, *mitigation* and *resilience* have been the primary focus in the literature with these topics in the top five research priorities through all time periods. Other topics that have also relatively stable research priorities include *water resources* ranking 12th in 1978–2010, 10th throughout 2011–2015 and 13th from 2016 to 2020 (Table 2).

Other topics have progressively increased as a research priority through the time periods, such as a*griculture* going from 6th (1978–2010) to 4th (2011–2015) to 3rd (2016–2020) and similarly *strategies* moving from 22nd (1978–2010) to 6th (2011–2015) to 5th (2016–2020). Research concerning *disaster risk reduction* (36th to 16th to 9th) and *sustainability* (18th to 13th to 7th) have increased considerably as priorities through time. Conversely, downtrends are observed for some topics such as *policy* dropping slightly from 7th (1978–2010) to 8th (2011–2015) to 10th (2016–2020), and *impacts* slipping from 5th (1978–2010) to 9th (2011–2015) to 21st (2016–2020). Research concerning *climate policy* (16th to 25th to 41st), *risks* (10th to 12th to 16th), *natural hazards* (26th to 44th to 47th) and *uncertainty* (19th to 20th to 24th) have also decreased in priority through the time periods. Interestingly, *small island*
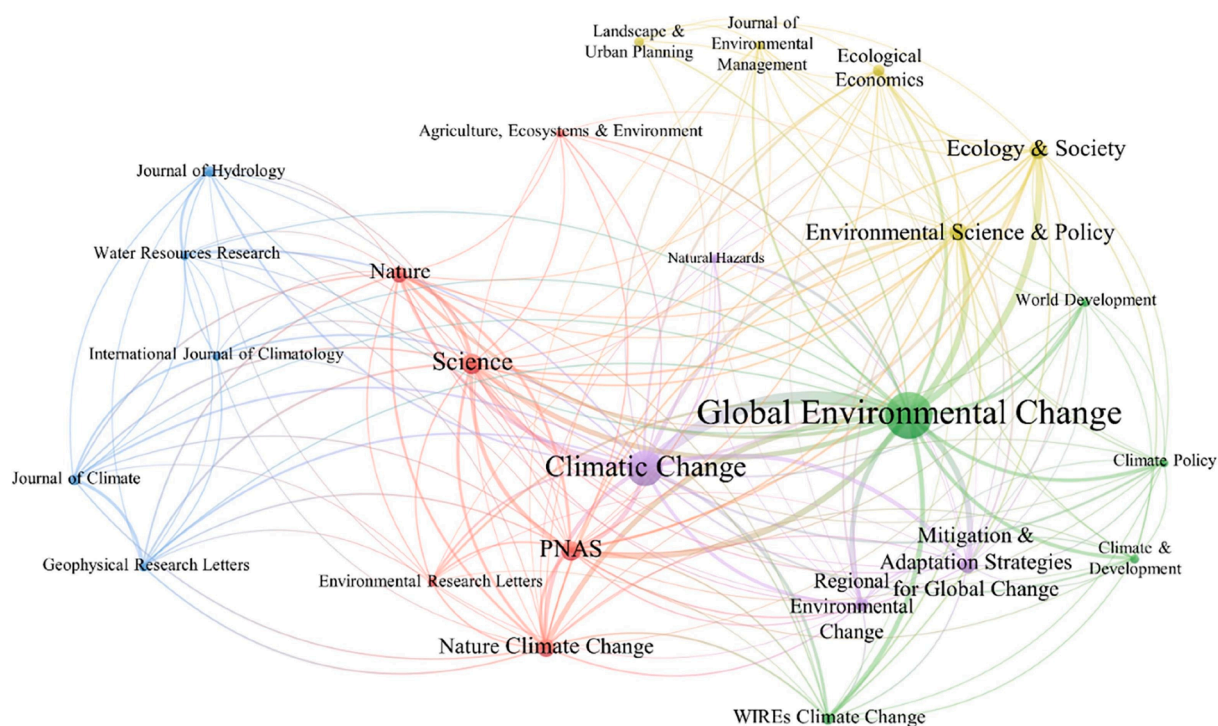
Fig. 7. Co-citation of the most commonly cited journals. Circle sizes are proportional to the number of citations per journal, while links represent publications that were co-cited in at least 1000 publications with the line thickness proportional to the strength of co-citation.

developing states was a major focus (49th) in the earlier phase, dropped in focus to 150th during 2011–2015 whereas since 2016, it has again become a priority focus (ranked 33rd).

New priority research topics have also been established during the emerging (2011–2015) and latest period (2016–2020). In the emerging period, there was a shift towards urban areas with novel topics such as *urban* (17th), *urban planning* (19th) and *urban heat island* (46th) developing as leading research priorities. As for the latest period (2016–2020), new priorities included *green infrastructure* (25th), *gender* (30th), *smallholder agriculture* (38th), *climate-smart agriculture services* (43rd), *participation* (48th), *urban resilience* (49th) and *finance* (50th). Overall, an ecosystem approach to climate change adaptation has risen in popularity, particularly in the last 5 years with more research focusing on *ecosystem services* (19th), *nature-based solutions* (37th), *ecosystem-based adaptation* (40th) and *socio-ecological systems* (46th).

Synonymous terms were clustered prior to analysis (S2 Table) and the terms 'climate change' and 'climate change adaptation' used to search for the literature were excluded.

3.6. Literature foundations

Evaluating the underlying knowledge base of this literature provides valuable insights into how the field of climate change adaptation has been shaped. This is achieved by analysing the cited reference lists of the 11,506 publications to distinguish key journals producing the underlying knowledge base as well as the leading publications underpinning this literature.

The most common journals cited in the underlying literature were *Global Environmental Change* (15,628 citations), followed by *Climatic Change* (10,790 citations), *Science* (5,108 citations), *Proceedings of the National Academy of Science of the United States (PNAS)* (4,937 citations) and *Ecology and Society* (4,300 citations) (Fig. 6, S5 Table). Comparing this to Fig. 4d of top 10 journals publishing on climate change adaptation provides insights into the quality of research produced by these journals. For example, although *Sustainability* is ranked 2nd in research output (Fig. 4d), publications from this journal are only cited 1,098 times, which places it outside the
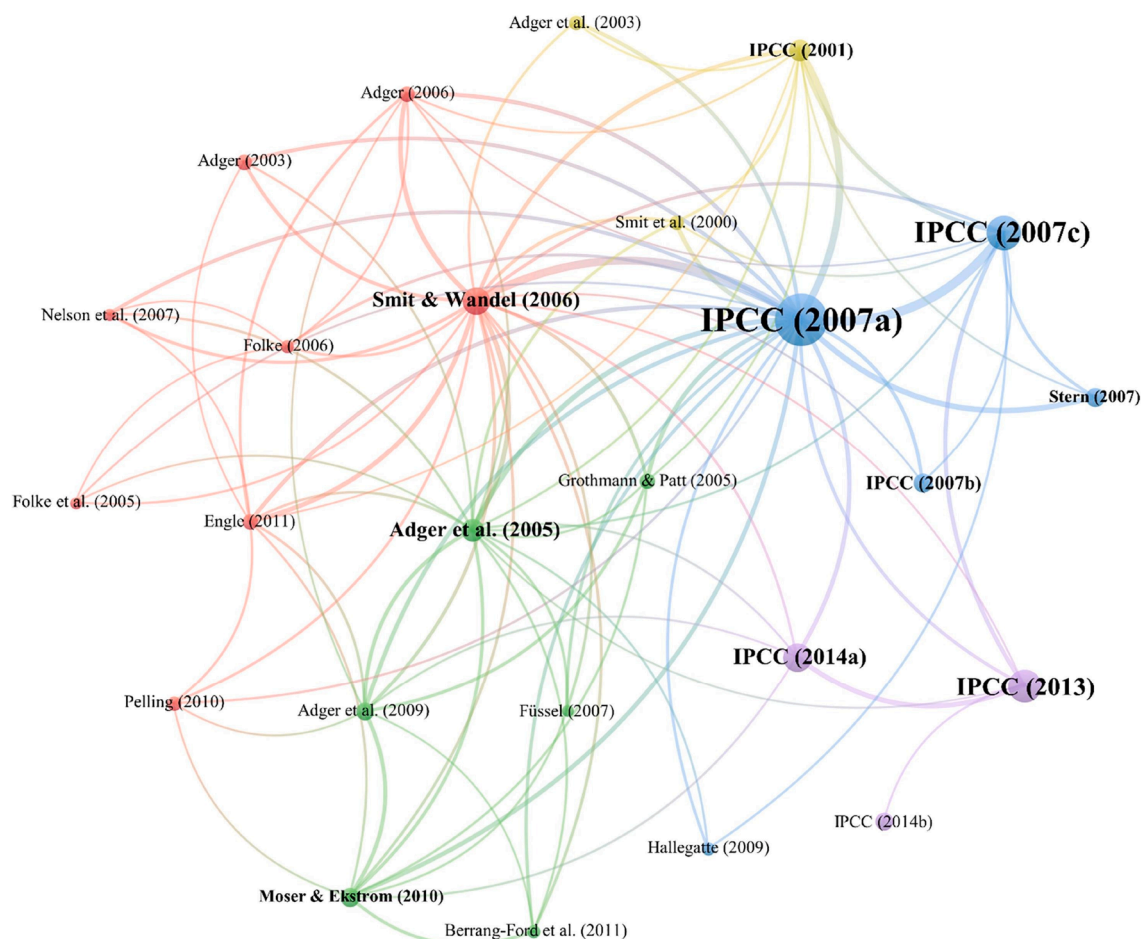
Fig. 8. Co-citation of the most commonly cited underlying literature. Circle sizes are proportional to the occurrence of each keyword, while co-occurrence links represent publications that were co-cited in at least 50 publications with the line thickness proportional to the strength of co-occurrence.

top 25 most cited foundational journals (Fig. 7). Research produced by high impact journals with a broad scope, such as *Nature, Science* and *PNAS*, has been integral to the development of this literature, and demonstrates the diversity of journals publishing on climate change adaptation.

There were a handful of foundational papers that have been highly cited across the 11,506 publications (Fig. 8). The most influential publications were produced by the IPCC, with the 2007 report on impacts, adaptation and vulnerability (IPCC, 2007a) cited by almost 16% of the literature (S6 Table). The next four most cited publications were also IPCC publications (IPCC, 2001, 2007a, 2013, 2014a) demonstrating the importance of these thorough and accessible international reviews. Smit and Wandel's (2006) seminal work on assessing adaptation, adaptive capacity and vulnerability was also central publication to the development of this literature (767 citations;6.7%). Similarly, Adger et al. (2005) was broadly co-cited with publications that focused on successful adaptation across scales (600 citations; 5.2%), as well as Stern (2007) (463 citations;4.0%) that focused on the economics of climate change, and Moser and Ekstrom (2010) (454;3.9%) which concerns barriers to climate change adaptation.

When publications from the cited reference lists were mapped, four co-citation clusters were apparent. The blue cluster contained several IPCC reports (IPCC, 2007a; 2007b; 2007c) as well as the research economics of climate change (Stern, 2007) and adaptation amidst uncertainty (Hallegatte, 2009). The red cluster focused on key concepts of climate change adaptation including vulnerability (Adger, 2006; Smit and Wandel, 2006), resilience (Folke, 2006; Folke et al., 2005; Nelson et al., 2007; Pelling, 2010) and adaptive capacity (Adger, 2003; Engle, 2011). The green cluster also focused on assessing the success of adaptation (Adger et al., 2005, 2009; Berrang-Ford et al., 2011; Grothmann and Patt, 2005; Moser and Ekstrom, 2010) as well as adaptation planning (Füssel, 2007). The yellow cluster contains research from the early 2000 s and focuses on the framework and foundations of climate change adaptation (Adger et al., 2003; Smit et al., 2000) in addition to the third assessment report on the impacts, adaptation and vulnerability (IPCC, 2001). Finally, the purple cluster contains the most recent IPCC assessment reports (IPCC, 2013; 2014a; 2014b).

4. Discussion

This paper has provided a broad overview of the overall trends in peer-reviewed climate adaptation science literature. Our analysis has looked at the geographical origins of adaptation science, co-authorships linkages, tracked changes in research priority themes over time and examined the foundational journals and papers that underlie the literature. Here we focus on unpacking our results with focus on three key areas: exponential growth and increased diversity of literature, temporal changes in focus and foundational literature, and cautions and opportunities of bibliometric methods to contribute to the evolving adaptation agenda.

4.1. Exponential growth and increased diversity

Our results demonstrate the global emergence of climate change adaptation science as adaptation studies have been published by almost every country and adaptation has become a mainstream research topic across journals, disciplines and sectors. Yet, despite this broad geographical and disciplinary focus, the adaptation science literature continues to be dominated by the five top countries (USA, UK, Australia, Germany and Canada) that together comprise 65.5% of all publications, raising questions about the representativeness of this knowledge. This dominance is not surprising given the capacities and early and long-term investments in climate change adaptation science across these countries. The USA has been an early investor in adaptation science, with also elevated climate change adaptation policy focus under the Obama Administration (Keskitalo and Preston, 2019). Likewise, UK's long-term Climate Impact Program (UKCIP) and associated policies and laws, and Australia's multi-million-dollar investments in the National Climate Change Adaptation Research Facility (hosted by Griffith University) have played a significant role. These countries also host many prominent scientists who have been working in the area for a long time.

While the trend of exponential growth in literature is well-known and discussed across the adaptation science community (Biesbroek et al., 2018; Keskitalo and Preston, 2019; Noble, 2019), our analysis quantifies its annual growth rate of 28.5%. Such exponential growth is clearly not unique to climate change adaptation: similar issues have been reported by Tonmoy et al. (2014) (77% increase in climate change vulnerability research during 2006–2011), Di Matteo et al. (2018) (rapid increase in climate change vulnerability assessment research during 2013–2016) and Haunschild et al.'s (2016, p. 16-17) observations that research on "adaptation, mitigation, risks and vulnerability of global warming" has grown exponentially since 2005. Furthermore, a recent review of broader climate change research demonstrated an average annual growth rate of 17.9% (Callaghan et al., 2020), yet climate change adaptation literature reviewed here is expanding considerably faster (28.5%). This growth alone shows how difficult it is for any one author or assessment process to remain fully up-to-date with the majority of the climate change adaptation literature, a familiar experience to most of us adaptation scholars. While previously we could have referred to "information deficit" (that we do not enough information about adaptation and that more information results in more action) (Preston et al., 2013), now the issue seems to be rather how to cope with, make sense of and synthesise this increasing amount of information in a helpful manner.

This rapid increase in publications has raised concerns whether the increase in quantity results in "literature chaff rather than nurturing grain" (Noble, 2019, p. 43), a sentiment echoed often in conversations especially on how to identify the most empirically valid learnings of this vast literature. Noble's observation presents us with an interesting question for debate: does the increased mainstreaming of adaptation across journals and disciplines lead to increased fragmentation of the knowledge base (Siders, 2019), leading to "reinventing the wheel", or does this mainstreaming actually increase diversity and innovation in adaptation science? In our analysis, the majority of authors ($N = 20,391$; 76.1%) have only authored one publication on climate change adaptation the remaining 23.9% of authors (6,417 authors with more than one) self-select to publish mainly on climate change adaptation and are likely to have more experience in this knowledge domain. Identifying the fundamental components of climate adaptation is indeed crucial in

developing a more robust adaptation science. But perhaps the most important aspect is whether we are asking the right questions that push the field forward and what those big bold questions are.

Tight co-authorship collaborative groups were evident amongst the top 60 authors. For example, the Ford-Smith-Berrang-Ford cluster has remained very separate from the majority of other authors while few key authors like Klein and Adger have collaborated more broadly. Such tight clustering in collaborations can result from shared social norms and trust that enable coordination and collaboration in scientific work (Lambiotte and Panzarasa, 2009). It can also stem from significant research investments resulting in large group hires at the same institution, and social relationships that are strengthened through existing social networks or even marriage. While such tight clustering is very typical in emerging knowledge domains (Becken, 2013), this can reduce innovation if authors do not expose their ideas to diverse views by working across domains (Epstein, 2019). Going forward, interrogating more closely the social collaborative relationships of the adaptation science community could provide important insights into which ideas and framings these clusters specifically champion for and which ideas, topics and methods are shut off from entering the research field.

4.2. Temporal changes in focus and foundational literature

Despite the rapid growth in recent years, the start of climate change adaptation literature was slow. As our results demonstrate, the early phase (1978–2010) saw only a handful of publications specifically focusing on climate adaptation. Several key developments in the 1990s, such as the publication of the first IPCC Assessment Report (1990) and 2nd Assessment report (1996) started bringing more focus on climate change overall while several climate specific journals were established during this period (Hulme, 2010). It is also well-known that adaptation to climate change as a specific area of research and policy did struggle to be considered alongside mitigation throughout the 1990s (Burton, 2009; Pielke Jr, 1998).

From 2000s onwards, several foundational papers on adaptation concepts (Adger, 2003, 2006; Smit et al., 1999; Smit et al., 2000; Smit and Wandel, 2006) emerged with also IPCC's 3rd assessment in 2001 and 4th assessment in 2007 that increased the focus on adaptation as a distinct field of research. Likewise, the Bali Action Plan agreed in 2007 under the UNFCCC is likely to have stemmed interest and increased research needs on climate adaptation at the global scale (Noble, 2019) as have significant extreme events such as Hurricane Katrina in the US, Al Gore's movie The Inconvenient Truth, and in particular IPCC's 4th Assessment that gave even more compelling evidence of the human influence in climatic changes and the importance of adaptation. Of influential papers, the Smith et al. (2000) paper set out many of these concepts and was highly influential charting these concepts also in IPCC's Third Assessment Report in 2001 (Schipper and Burton, 2009). These papers and IPCC reports remain key foundations of the current climate adaptation science literature. In fact, Giupponi and Biscaro's (2015) report that research often surges on particular themes identified as knowledge gaps in IPCC assessments as was the case with the Special Report on Extremes (SREX) that heralded new focus on the interlinkages between climate change adaptation and disaster risk reduction.

While core concepts, such as *vulnerability*, *resilience* and *adaptive capacity* have remained central, new priorities such as *green infrastructure*, *gender*, and *ecosystem-based adaptation*, have emerged only recently. The last period (2016–2020) in particular has seen a strong interest in *urban* adaptation research while also *small island developing states* research has increased in profile. Renewed focus has been also on *agriculture*, *small holders* and *perceptions* in particular in *Africa* and in *developing countries,* likely as a response to the need to document views and experiences on the ground. Surprisingly, topics such as *migration* that was a focus in the emerging phase no longer occupy a top research focus even if discussions around climate security, climate refugees and conflict have emerged as key issues across many UN led platforms and NGO initiatives. Interestingly, *resilience* has become the most dominant keyword in the last five years.

The emergence of new research topics can be linked to global policy agendas, scientific advances and increase attention paid by global funding bodies and organisations to the issue of adaptation. For example, concepts such as *ecosystem-based adaptation* crossed over from Convention on Biological Diversity (CBD) in 2009 to gain more prominence in climate change and now form an important focus within adaptation science (Noble, 2019; Ojea, 2015), with strong linkages to urban settings. New climate funds, such as the Adaptation Fund and Green Climate Fund, and increased availability of climate finance overall have generated also new research needs under the UNFCC (Schipper and Burton, 2009) while connecting the adaptation science community more closely to adaptation practice.

Therefore, it is important to note that the adaptation science literature has not evolved in isolation but is very much connected to adaptation policy and practice and influenced by broader societal trends in key issues, challenges and global events. For example, several key topics do not yet feature in the top 50 or 100 yet but are already identified as key topics needing more consideration in research, policy and practice. These include for example climate justice and equity (Boeckmann and Zeeb, 2016), climate resilient development pathways, maladaptation (Eriksen et al., 2021), limits to adaptation, loss and damage (Mechler et al., 2020), psychological dimensions of adaptation, post-colonial approaches and Indigenous knowledge (Parsons et al., 2019), adaptation pathways (Magnan et al., 2020), feasibility and effectiveness (Singh et al., 2020; Siders, 2019), tracking of adaptation metrics, the global goal of adaptation (Persson, 2019) and transformation (Schipper et al., 2020) that all provide critical entry points to adaptation. Likewise, new technologies such as Artificial Intelligence (AI), machine learning, blockchain and crypto currencies are all changing the ways decisions are made globally, as are also social and political movements, the challenges with pandemics like COVID-19, and the emergence of adaptation as a global governance issue. Understanding these and other emerging trends will remain crucial in driving the adaptation science agenda forward.

4.3. Cautions and limitations in reviewing adaptation literature

Even though bibliometric methods enable analysis of large quantities of data as we have demonstrated in this paper, the results

must be treated with some caution. For example, geographical biases are embedded in the databases reporting structures that can impact on e.g. geographical representation of authors and institutions (Biesbroek et al., 2013). In terms of showing disciplinary trends (Fig. 4a), papers can have multiple discipline categories that are assigned by Scopus and Web of Science librarians and do not necessarily always reflect the authors' preference. Yet, our analysis has focused on what terms authors themselves are using to brand their research. Hence, the analysis of major trends and keywords as research priorities reflects the social construction of the field by authors.

Conducting a robust bibliometric review of any scientific field requires intimate working knowledge of the field itself in order to analyse a field and contribute to its progress, one must be intimately connected with it (Frost, 1986). Mastering a software program is another matter from knowing the underlying intellectual historical and current debates that have shaped the field and the social relationships in knowledge production that underpin collaborations and push particular ideas forward and close off others. For example, Wang et al.'s (2018) earlier study on bibliometric analysis on climate adaptation uses such broad search terms (including greenhouse gases, global warming) that their list of top authors and foundational papers is hardly recognisable for those working on climate change adaptation science. Therefore, our analysis has been solely focused on the different variants of "climate change adaptation" in order to capture those authors who explicitly identify climate change adaptation as the priority topic of their research.

There are several issues that we considered during this study as worthwhile considerations but where the method did not support robust analysis. For example, we were not able to analyse such factors as author gender given that this information is not part of the general publication submission process and hence does not allow for easy trend generation from databases. Also, we had to make a choice in search queries where we tried to include initially biological adaptation. Yet, this brought in significant bycatch of papers unrelated to climate change adaptation which led us to focus more on the human dimensions literature. We also recognise that focusing only on peer-reviewed climate adaptation literature leaves out vast amount of knowledge. Hence, while our aim was to understand the internal trends within academic literature, the exploration of grey literature and its rich contributions will strengthen insights on climate adaptation and could be done via other methods such as more extensive use of machine learning that can handle even larger datasets (see eg Callaghan et al., 2020). We also found that this bibliographic method is not well posed to analyse trends in "tail end" topics, which are emerging but not yet prominent trends across the literature. Yet, identifying in more detail in particular emerging trends is a key area of innovation. Our plan is to conduct expert elicitation with leading adaptation scholars on this topic and then run through the list of emerging trends within our database to investigate the extent that these trends are or are not prevalent in the adaptation literature.

Even if this literature is growing rapidly, several activities demonstrate that there is global movement in the consolidation of adaptation science community. The development of adaptation curriculums, degrees and certification is already taking place that can identify the core knowledge necessary for adaptation professionals to learn what adaptation is and how to do it well. Global platforms and organizations such as Adaptation Futures series, Global Commission on Adaptation, World Adaptation Science Program, Adaptation Gap Report and the recently launched Adaptation Research Alliance are starting to drive more critical and reflective debates on where we should be heading, what the key questions are that we should be asking, and how the adaptation science enterprise can support adaptation policy and practice that is inclusive and just. Likewise, an increasing number of scholars are starting to question the core concepts used in climate adaptation and pinpointing areas where we need to challenge the conventional (Eriksen et al., 2021; Moser et al., 2019a; Preston et al., 2015; Schipper et al., 2020) wisdom. All of these endeavours support the coming together of the global adaptation science community and can help us to move towards a more reflective and unified adaptation theory and science that build on innovation and diversity of knowledge and experience. This requires however a more coordinated approach in identifying the fundamentals of robust climate adaptation that work across different contexts and more attention to the development of methodological rigour and innovation.

5. Conclusion

This paper has investigated the evolution of and current trends in peer-reviewed climate adaptation science. By using a bibliometric method, we have captured geographical representation, temporal trends in research priority topics and provided a review of the most cited papers, authors, foundational journals and research collaboration clusters. Overall, the subject of climate change adaptation is now truly global in its reach given its mainstreaming across journals, sectors and disciplines combined with rapid annual growth rate that is set to continue. The key topics have clearly diversified over time with new topics such as ecosystem-based adaptation and green infrastructure in particular in the last five years.

Yet, despite this diversification and mainstreaming of climate adaptation science, the literature is still heavily dominated by developed countries. This leads to a pressing need to increase especially developing country contributions to this vast literature so that it adequately reflects the diversity of climate adaptation insights and experiences. Future research could also look into similar trends in grey literature to capture the implementation experiences across the world and provide additional insights into how adaptation has evolved as a topic over time and identify future directions on emerging trends that are relevant to adaptation science, policy and practice.

Declaration of Competing Interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crm.2021.100290.

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