

Scholarly networks on resilience, vulnerability and adaptation within the human dimensions of global environmental change

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Abstract

This paper presents the results of a bibliometric analysis of the knowledge domains *resilience*, *vulnerability* and *adaptation* within the research activities on human dimensions of global environmental change. We analyzed how 2286 publications between 1967 and 2005 are related in terms of co-authorship relations, and citation relations.

The number of publications in the three knowledge domains increased rapidly between 1995 and 2005. However, the resilience knowledge domain is only weakly connected with the other two domains in terms of co-authorships and citations. The resilience knowledge domain has a background in ecology and mathematics with a focus on theoretical models, while the vulnerability and adaptation knowledge domains have a background in geography and natural hazards research with a focus on case studies and climate change research. There is an increasing number of cross citations and papers classified in multiple knowledge domains. This seems to indicate an increasing integration of the different knowledge domains.

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1. Introduction

In recent years, the concepts¹ of *resilience*, *vulnerability* and *adaptation* have increasingly been used in the research on the human dimensions of global environmental change (HDGEC). We are interested in identifying the structure and dynamics of major fields contributing to the particular concepts within the research on HDGEC. We intend to identify the most influential scholars, publications, and

journals in the knowledge domains resilience, vulnerability and adaptation. We wondered whether the knowledge domains were mainly acting independently, whether there was much cross fertilization, and how this has changed over time?

The study on HDGEC is performed by scholars from many different disciplines, including geography, political science, economics, ecology, environmental science, psychology, archaeology, mathematics, etc. In recent years, reviews have appeared on separate knowledge domains, such as by Gunderson (2000), Cutter (2003), and Smit et al. (1999, 2000). Four other papers in this special issue of Global Environmental Change discuss the theoretical and methodological developments of the concepts of resilience, vulnerability and adaptation with regard to HDGEC (Folke, 2006; Adger, 2006; Smit and Wandel, 2006), as well as their conceptual similarities and differences (Gallopín, 2006).

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¹These concepts are defined as a cross-cutting theme of the International Human Dimensions Programme on Global Environmental Change (IHDP). These concepts can have different meanings to different scholars. For example, “ecological resilience”, “engineering resilience” and “social resilience” are covered by “resilience” (Holling, 1996; Adger, 2000).

The concept of *resilience* was introduced by Holling (1973) in the field of ecology. According to Holling (1973, p. 17) “resilience determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb change of state variable, driving variables, and parameters, and still persist”. Originally, resilience was used in the field of population ecology and in the study on managing ecosystems. As such, it is mathematically based and model oriented. Since the late 1980s, the concept has been used increasingly in the analysis of human–environmental interactions. A number of scholars working on the resilience of social–ecological systems have organized themselves since 1999, forming the Resilience Alliance.

The concept of *vulnerability* has its roots in the study on natural hazards. Vulnerability is defined as “the characteristics of a person or group in terms of their capacity to anticipate, cope with, resist, and recover from the impact of a natural hazard. It involves a combination of factors that determine the degree to which someone’s life and livelihood is put at risk by a discrete and identifiable event in nature or in society” (Blaikie et al., 1994, p. 9). In the 1990s, natural hazards scholars started to focus on the vulnerability of people to impacts of environmental change, especially climate change. There is a disciplinary legacy of geography. In contrast to resilience, there has been little (Ionescu et al., 2006) focus on mathematical models, but more on the comparative analysis of case studies.

Adaptation of humans to environmental variability was a focus of anthropology since the early 1900s. In the 1990s, scholars began to use the term adaptation for the study on the consequences of human-induced climatic change, without explicitly relating this back to these conceptual origins in anthropology. The Intergovernmental Panel on Climate Change defines adaptation as “adjustment in ecological, social, or economic systems in response to actual or expected climatic stimuli and their effects or impacts. This term refers to changes in processes, practices, or structures to moderate or offset potential damages or to take advantage of opportunities associated with changes in climate. It involves adjustments to reduce the vulnerability of communities, regions, or activities to climatic change and variability” (McCarthy et al., 2001, p. 643).

A manual compilation and systematic review of all publications on resilience, vulnerability and adaptation seems to be impossible due to the large amount of papers and books published between 1960 and 2005 and the diversity of the scientific disciplines involved. Here we present a bibliometric analysis of the three knowledge domains by using tools and techniques developed for the large-scale mapping of knowledge domains (Börner et al., 2003; Shiffrin and Börner, 2004). This analysis requires the acquisition of a high-quality, comprehensive dataset of relevant papers, the analysis and correlation of these paper records, and the visualization of the results for means of communication. In particular, our goal is to objectively identify major research topics, experts, papers, etc., in the

three knowledge domains of interest. In addition, we would like to identify interconnections of research outputs between the three knowledge domains.

The remainder of this paper presents the results of analyzing 2286 publications related to the study on resilience, vulnerability and adaptation as published between 1967 and 2005. These publications are mainly articles in international journal in English due to the way we collect our data. General statistics are provided; major journals, most productive authors and best connected authors are identified; and co-author and paper citation networks for the three areas as well as for the complete dataset are presented and discussed. Last but not least, we tried to answer if the different scientific communities interact and overlap more (leading to a merge of the fields) or less (due to an increasing flood of information and corresponding specialization) over time.

2. Data collection

Most research results in the domains of resilience, vulnerability and adaptation are published in journals. The *Arts and Humanities Index*, the *Social Science Citation Index* and the *Science Citation Index* as provided by the Institute of Scientific Information (ISI) were used to acquire raw material for the bibliometric analysis. A manual check of ISI’s journal coverage confirmed that all relevant journals were covered.

The data were retrieved from ISI’s *Web of Science* online interface (<http://www.isiknowledge.com>) between October 4 and 14, 2004. On the basis of expert feedback on a draft of this paper, additional data were downloaded between March 14 and 20, 2005. For each paper, information on the complete author, title, language, abstract, keywords, address, cited references, times cited, publisher information and subject category was saved. Two types of searches were performed: (1) a keyword-based search and (2) a cited reference search using seminal papers.

2.1. Keyword-based search

In collaboration with domain experts (see Acknowledgements), we created a set of keywords that cover major dimensions of research on global environmental change. The complete set of keywords used to retrieve papers on resilience, vulnerability and adaptation within the area of HDGEC is given in Table 1.

2.2. Cited reference search

A set of seminal papers, also called ‘seeds’, which are referred to frequently by scholars publishing on resilience, vulnerability and adaptations in HDGEC, was identified in consultation with various experts in the field (see Acknowledgements). These seeds include books, journal articles, and other types of papers and are given in Table 2.

Table 1
Keyword combinations used to retrieve papers for the three knowledge domains

Resilience	Vulnerability	Adaptation
Resilience & adaptation	Vulnerability & adaptation	Adaptation & vulnerability
Resilience & vulnerability	Vulnerability & resilience	Adaptation & resilience
Resilience & coastal	Vulnerability & coastal	Adaptation & coastal
Resilience & coral	Vulnerability & coral	Adaptation & coral
Resilience & eutrophication	Vulnerability & eutrophication	Adaptation & eutrophication
Resilience & desertification	Vulnerability & desertification	Adaptation & desertification
Resilience & global change	Vulnerability & global change	Adaptation & global change
Resilience & deforestation	Vulnerability & deforestation	Adaptation & deforestation
Resilience & climatic change	Vulnerability & climatic change	Adaptation & climatic change
Resilience & climate change	Vulnerability & climate change	Adaptation & climate change
Resilience & environmental change	Vulnerability & environmental change	Adaptation & environmental change
Resilience & land use change	Vulnerability & land use change	Adaptation & land use change
Resilience & food security	Vulnerability & food security	Adaptation & food security
Ecological resilience	Ecological vulnerability	Adaptation & human ecology
Social resilience	Social vulnerability	Adaptation & climate policy
Resilience assessment	Vulnerability assessment	Social adaptation
	Human security ^a	Social adaptability
	Environmental security ^a	Human adaptation
		Human adaptability
		Adaptive response
		Adaptive capacity
		Adaptive strategies
		Human biology ^a
		Adaptation & environment ^a (only social science and humanity)
		Adaptability & environment ^a (only social science and humanity)

^aAdded in the second round of information retrieval in March 2005.

Table 2
Seminal papers used to retrieve papers for the three knowledge domains based on cited reference search

Resilience	Vulnerability	Adaptation
Holling (1973)	White and Haas (1975)	Rappaport (1967) ^a
May (1977)	Burton et al. (1978)	Rappaport (1977)
Ludwig et al. (1978)	Sen (1981)	Butzer (1980)
Timmerman (1981)	Timmerman (1981)	Timmerman (1981)
Walker et al. (1981)	Clark (1985)	Rosenberg (1992)
Pimm (1984)	Chambers (1989)	Easterling (1996)
Holling (1986)	Swift (1989)	Smit et al. (1996)
Gunderson et al. (1995)	Dow (1992)	Watson et al. (1996)
Berkes and Folke (1998)	Liverman (1990)	Smithers and Smit (1997)
Adger (2000)	Watts and Bohle (1993)	Smit et al. (1999)
Scheffer et al. (2001)	Bohle et al. (1994)	Tol et al. (1998)
Gunderson and Holling (2002)	Blaikie et al. (1994)	Smit et al. (2000)
Berkes et al. (2003)	Kasperson et al. (1995)	McCarthy et al. (2001)
	Cutter (1996)	
	Ribot et al. (1996)	
	Watson et al. (1996)	
	Hewitt (1997)	
	Watson et al. (1998)	
	Adger (1999)	
	Klein and Nicholls (1999)	
	McCarthy et al. (2001)	
	Kates et al. (2001)	

^aAdded in the second round of information retrieval in March 2005.

One seed is handled in a special way. The book by Sen (1981) is highly cited in various study areas related to poverty. Also within the study on vulnerability, it was used as a major source. Due to the large number (more than 400) of citations of Sen's (1981) book in the ISI database, of which many are not directly related to vulnerability, we decided to include only publications referring Sen (1981) when they also use the word "vulnerability" in the title, abstract or keywords.

2.3. Data cleaning

The title, keywords and abstract of each document that were retrieved by keyword-based and cited reference search were checked manually and independently by two experts, the first two authors of this article. Only publications in the area of human dimensions of environmental change were kept. Studies which focused exclusively on ecological dynamics (such as the resilience of plankton communities) or on social dynamics (such as the adaptation of organizations) were excluded. The decision to include or exclude a publication in the database was based on the information provided in the title and abstract of the publication. When in doubt, the publication was included. Only the 2286 papers relevant to the area of human dimensions of environmental change were kept. All data collection and manual cleaning was performed by the first

two authors. For each knowledge domain, one researcher used seed documents and the other used keywords, so that many publications have been evaluated by two researchers independently to determine whether it needed to be included or not. Publications listed as book reviews were excluded.

Subsequently, all retrieved papers as well as the seeds were loaded onto an MS Access database for further data cleaning to eliminate duplicate records and unify different spellings of authors' names.

A number of very specific decisions were made. For example, the paper by Arrow et al. (1995) was published first in *Science* on April 28, 1995, and was reprinted in November 1995 in *Ecological Economics* and in February 1996 in *Ecological Applications*. We decided to keep only the *Science* paper and to count citations to the other versions as citations to the original *Science* paper. Other data cleaning details are provided on a supplementary webpage available online at <http://www.public.asu.edu/~majansse/pubs/SupplementIHDP.htm>

2.4. Discussion of the dataset

The acquired dataset has a number of potential shortcomings. It mostly covers journal papers, especially those published in English. Relevant books and book chapters might have been missed as they are not included in the ISI database. The non-English literature is largely excluded by using the ISI database. This might introduce bias for particular streams of research. A second issue is the coverage of the dataset. The concepts of resilience, vulnerability and adaptation have developed over time, and have been used in various ways, often unrelated to the study on HDGEC. Relevant papers that did not use the keywords given in Table 1 or did not cite the seeds listed in Table 2 were not retrieved.

In sum, while we aimed for the best and most complete set of relevant publications, we might have missed important contributions. Still, we believe we have a comprehensive dataset that covers the three areas well and can be used to analyze the structure and dynamics of research on resilience, vulnerability and adaptation within the area of HDGEC.

3. Data analysis and visualization

3.1. General statistics

The final dataset contains 2266 unique journal papers and 20 books and other non-journal publications published between 1967 and 2005. From those, 1084 report research on resilience, 939 are related to research in vulnerability, and 650 discuss research on adaptation. Some papers are classified into two or all three knowledge domains: 78 in adaptation and resilience, 258 in adaptation and vulnerability, 95 in resilience and vulnerability, and 44 in all three. In recent years, more papers seem to make

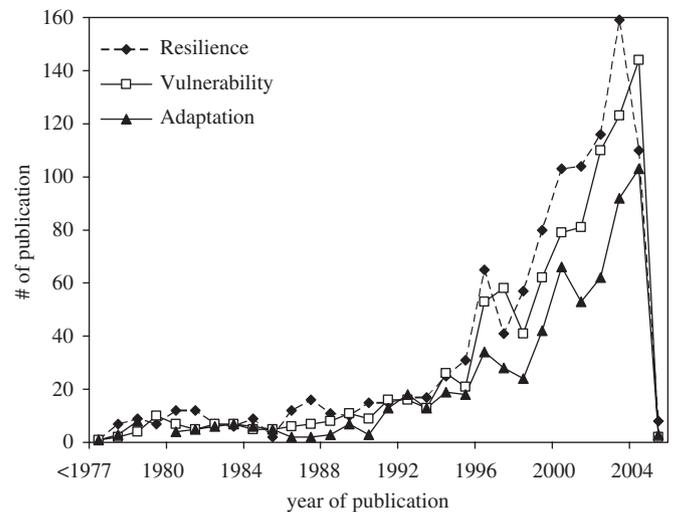


Fig. 1. Papers published in the three knowledge domains per year. Data for 2004 and 2005 are incomplete.

contributions to more than one knowledge domain, as we will discuss later.

Fig. 1 shows the number of papers in the three knowledge domains between 1977 and 2005. There appears to be a stable number of papers for all three areas till the early 1990s, after which the number of papers increases rapidly. This is surprising, as an analysis of all ISI data on papers shows a linear increase in papers over time (Boyack and Bäcker, 2004). This sharp increase in publications coincides with the increased interest in global environmental change, especially human-induced climatic change around the same time. Furthermore, during the 1990s, various institutions and networks started functioning, such as the International Human Dimensions Programme on Global Environmental Change (IHDP), Resilience Alliance, Sustainability Science group (organized in 2000–01), and Beijer International Institute of Ecological Economics (organized in 1991). Whether the creation of networks and institutions is responsible for the sharp increase in publications cannot be answered by the information available.

A closer examination of the dataset reveals that the number of authors per paper increased from 1.5 authors to 2.5 authors per paper between the 1970s and early 2000s. This might be a consequence of more collaboration, for example, via international interdisciplinary networks. This trend is similar for all three knowledge domains and is consistent with the trend in various disciplines (Guimerà et al., 2005).

3.2. Journal statistics

Which journals have published many articles in the various knowledge domains and which journals got most citations? When we exclude the 20 books and other non-journal publications, we have 2266 papers, which have

Table 3
Top 10 journals with the largest number of papers (left) and the highest number of citations (right) within the whole database, over the period 1977–2005

Papers published 1977–2005		Paper cited 1977–2005	
Journal	No. of articles	Journal	No. of citations (no. of articles)
1 Climatic Change	96	Annual. Review of Ecology	400 (8)
2 Global Environmental Change	74	Climatic Change	334 (96)
3 Climate Research	62	Nature	289 (16)
4 Ecological Economics	58	Global Environmental. Change	258 (74)
5 Environmental Management	57	Ecosystems	199 (29)
6 Ambio	50	Science	158 (18)
7 Ecological Applications	34	Journal of Range Management	135 (11)
8 Human Ecology	31	Ecological Applications	135 (34)
9 Conservation Ecology	30	Ambio	123 (50)
10 Ecosystems, Environmental Monitoring and Assessment	29	Progress in Human Geography	94 (11)

been published in about 568 different journals. This shows a disperse nature of the research topics covered in this paper.

Table 3 (left) lists the top 10 journals in which most papers have been published. On top of the list are climatic change-oriented journals, followed by ecology and ecosystem management-oriented journals. Note that a number of these journals (e.g., Global Environmental Change, Conservation Ecology,² Ecosystems) were created after 1990. If only publications from 2000 onwards are taken into consideration, the journals Climatic Change, Global Environmental Change, Ecological Economics, Conservation Ecology, Ambio and Environmental Monitoring and Assessment have published the most in these domains.

Table 3 (right) shows citation counts per journal, compiled using the *HistCite*^{TM3} software (Garfield, 2004). Note that these counts represent citations by and to publications within the set of 2266 papers. The most cited journal is the Annual Review of Ecology and Systematics; however, this ranking is primarily due to its publication of the most highly cited paper in this analysis—Holling (1973).

²Conservation Ecology was renamed Ecology and Society in 2004. However, Ecology and Society was not yet included in the ISI database at the time of data collection.

³We used *HistCite* version 2004.11.12.

Table 4 shows the top 10 journals that have the highest number of papers published in each of the three knowledge domains. Resilience-oriented papers are mainly published in ecology- and ecosystem management-oriented journals, which are quite different from the other two knowledge domains. The list of journals for papers on vulnerability shows that this concept has a background in geography (Annals of the American Association for Geography and natural hazard research (Disasters, Natural Hazards). The list of journals for papers on adaptation shows its roots in anthropology (American Anthropology, Human Ecology, Current Anthropology) and the current focus of climate and global change research on adaptation. Climate change-oriented journals are frequently used to disseminate research results in vulnerability and adaptation.

Using *HistCite*TM, we ranked the journals according to their citation counts (analogous to Table 3) separately for each knowledge domain. Table 5 shows the dominance of ecology journals for the domain resilience, and geography and climate change for vulnerability and adaptation. We also see two journals on development studies in the domain of vulnerability (World Development, and the Institute for Development Studies (IDS) Bulletin).

3.3. Author statistics

Next, we were interested in identifying and analyzing the most productive and most collaborative authors within our database (including the 20 publications we excluded in the journal analysis). Some of the seeds in Table 2 are edited volumes, and for these publications only the editors have been included in the author statistics. Table 6 shows the top 10 authors who have the highest number of publications (left) and the highest number of citations (right) in our dataset. Professor Folke (Department of Systems Ecology at Stockholm University) leads with the highest number of publications. We used *HistCite*TM to calculate the number of times authors are cited. C.S. Holling, currently Emeritus Professor at the University of Florida, and previously at University of British Columbia (Canada) and the International Institute for Applied Systems Analysis (Austria), is by far the most cited author, followed by Folke.

Table 7 presents the most productive institutions and countries. Papers are allocated to institutions and countries on the basis of the affiliations of the first author. The most productive institution is Stockholm University, where Folke is Professor. Following institutions are Wisconsin University (Carpenter), CSIRO (Walker), University of East Anglia (Adger), UBC (Holling), and the University of Florida (Holling). The most productive countries (as measured by affiliation of first author) are USA, UK, and Canada. Since 97% of the papers are published in English, it is no surprise that the most productive countries are native English-speaking countries.

By using *HistCite*TM, highly cited papers that are not part of our database were identified. These are Holling (1978) with 135 citations, Walters (1986) with 121, Ostrom

Table 4
Top 10 journals with the largest number of papers in resilience, vulnerability and adaptation, over the period 1977–2005

Resilience			Vulnerability		Adaptation	
Journal	No. of papers	Journal	No. of papers	Journal	No. of papers	
1	Ecological Economics	57	Climatic Change	61	Climatic Change	57
2	Environmental Management.	44	Global Environmental Change	52	Global Environmental Change	44
3	Ambio	37	Climate Research	46	Climate Research	34
4	Ecological Applications	31	Annals of the American Association of Geographers	23	American Anthropology	15
5	Conservation Ecology	28	Disasters	23	Human Ecology	14
6	Ecosystems	28	Water, Air and Soil Pollution	17	Environmental Monitoring & Assessment	12
7	Ecological Modelling	21	Ambio	16	Climate Policy	12
8	Conservation Biology	16	Environmental Monitoring & Ass	16	Building Research	9
9	Forest Ecology and Management	16	Ocean & Coastal Management	14	Ecological Economics	9
10	Journal of Environmental Management	15	Natural Hazards, Climate Policy	13	IDS Bulletin, Current Anthropology, Water Air and Soil Pollution	8

Table 5
Top 10 journals with the largest number of citations in resilience, vulnerability and adaptation, over the period 1977–2005

Resilience			Vulnerability		Adaptation	
Journal	No. of received papers	Journal	No. of received papers	Journal	No. of received papers	
1	Annual Review of Ecology	398 (8)	Global Environmental Change	154 (52)	Climatic Change	189 (57)
2	Nature	263 (8)	Climatic Change	152 (61)	Global Environmental Change	113 (44)
3	Ecosystems	180 (28)	Progress in Human Geography	80 (8)	Climatic Research	28 (34)
4	Journal of Range Management	130 (11)	IDS Bulletin	74 (12)	Agricultural and Forest Meteorology	24 (5)
5	Ecological Applications	114 (31)	Science	53 (6)	Progress In Human Geography	19 (4)
6	Ambio	94 (37)	Annals of the American Association of Geographers	50 (23)	Building Research & Info	17 (9)
7	Science	80 (12)	Climate Research	37 (46)	Professional Geographer	15 (3)
8	Journal of Ecology	66 (3)	World Development	34 (8)	Ambio	14 (7)
9	Ecological Economics	64 (51)	Ambio	25 (16)	Environmental Monitoring & Assessment	14 (12)
10	Conservation Biology	62 (16)	Geoforum, Environmental Monitoring & Assessment, Disasters	23 (8, 16, 23)	Nature, American Anthropology	12 (6, 15)

The figures in parentheses are the number of articles in that journal in that knowledge domain.

(1990) with 110, Hardin (1968) with 77, Ludwig et al. (1993) with 73, Blaikie and Brookfield (1987) with 68, Vitousek et al. (1997) with 60, Costanza R d'Arge et al. (1997) with 55, Rosenzweig and Parry (1994) with 52 and Levin (1992) with 45 citations. The reason that they are not included is that some of them are not in the ISI Web of Knowledge (books, and papers before 1977) and were not used as seeds. Those who are in the ISI Web of Knowledge,

and are not included in our database, did not refer to seed publications and/or use the keywords given above.

3.4. Co-author networks

Next, we were interested in understanding the scholarly interactions and the structure of the research community based on co-authorship relations. A total of 3860 unique

Table 6
Top 10 authors of the complete dataset

Number of publications		Number of times cited		
Author	No. of publications	Author	No. of citations	
1	C. Folke	50	C.S. Holling	1280
2	C.S. Holling	23	C. Folke	481
3	S.R. Carpenter	20	L.H. Gunderson	325
4	B.H. Walker	19	B.H. Walker	307
5	F. Berkes	17	R.W. Kates	229
6	C. Perrings	16	F. Berkes	229
7	J.B. Smith	15	S.S. Light	218
8	W.N. Adger	14	I. Burton	188
9	R.W. Kates	14	G.F. White	183
10	B.L. Turner	14	S.R. Carpenter	183

The left part of the table lists the authors with the most publications. The right part of the table shows the authors with the largest number of citations.

Table 7
Top 10 highly productive institutions (left) and countries (right)

Number of publications		Number of publications		
Institution	No. of publications	Country	No. of publications	
1	Stockholm University	69	USA	1045
2	University of Wisconsin	60	UK	282
3	CSIRO	58	Canada	272
4	University of East Anglia	53	Australia	152
5	University of British Columbia	51	Netherlands	116
6	University of Florida	38	Sweden	112
7	Wageningen University	38	Germany	69
8	University of Guelph	35	France	62
9	University of Colorado	33	South Africa	46
10	Royal Swedish Academy, US EPA	32	India	39

The publications are distributed to the institutions and countries of the lead author. For 91 publications, this information was not available.

authors and 10,286 co-authorship relations were identified in the complete dataset. By representing authors as nodes and their co-authorship relations as edges, the links between nodes and co-author networks can be analyzed and visualized. This visualization is of interest, as it may help us to identify structures of collaboration between authors.

Different thresholds were applied to identify and map the most productive authors, the best connected authors

and the strongest co-authorship relations. In particular, we identified all nine authors who had at least 50 unique co-authors. Next, we selected the 17 most productive authors with a minimum of 10 papers. Both sets make up the set of 22 authors who are very productive and/or collaborative. Next, we determined all co-authors for those 22 authors, but kept only those 67 authors who had a minimum of five papers. The thresholds were manually selected such that the number of authors and their co-authorships was sufficiently large to derive meaningful structures. We balanced the desire to provide a lot of data points, but not too many in order to be identifiable nodes. We acknowledge that this procedure is somewhat subjective, but small changes in the thresholds had no significant impact on the structure of the network, only the visual transparency.

The resulting network was laid out using the Pajek (Batagelj and Mrvar, 1997) network visualization package (Fig. 2). The most densely linked group of authors around the Folke node publishes in the domain of resilience. This densely linked group consists mainly of members of the Resilience Alliance (RA) and scholars affiliated with the Beijer International Institute of Ecological Economics. The other knowledge domains are more dispersed.

Next, we wanted to examine the correlation between international research networks and co-authorship networks. Although we cannot identify the precise causal relationships (was it the network that stimulated co-authorships or the other way around), it did provide us with some indication of the position of scholars of different networks in the knowledge domains. We analyzed the participation of authors in various international research networks, like IHDP, Intergovernmental Panel on Climatic Change (IPCC), Sustainability Science (SS) and RA. An author is defined to be participating when (s)he is listed as an author or reviewer in McCarthy et al. (2001), the <http://www.ihdp.uni-bonn.de/html/who/whoiswho.html> (accessed on January 13, 2005), is a board member of the RA in 2004, or is listed in the research group on SS (see <http://sust.harvard.edu/people.htm>; accessed on January 12, 2005).

Fig. 3 shows four networks that have the layout identical as shown in Fig. 2, but are color coded according to the author's participation in IHDP, IPCC, SS and RA. Author nodes are given in white when the author is not listed as an official member and are colored otherwise. The author with the most formal participations (three) in the international networks is William Clark, Harvard University and former graduate student of C.S. Holling.

We see that RA and SS, which are self-organized research networks, are clustered in a small area of the author network space. IPCC and IHDP cover a larger part of the whole co-author network, although we also see clusters in those networks. Future analysis of different dates of the co-authorship networks may illuminate whether the creation of international networks affected the structure of co-authorship networks.

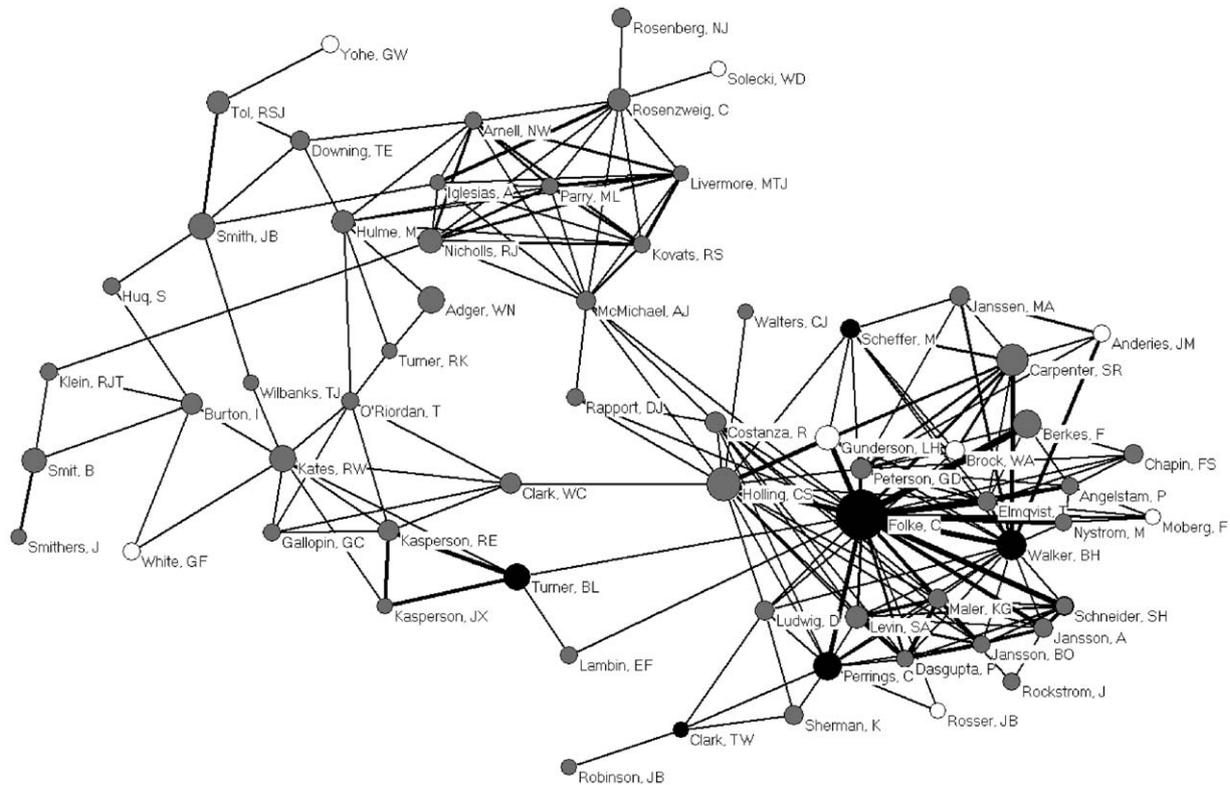


Fig. 2. Co-author network of most productive and best connected authors with the strongest co-authorship relations. Circles denote author nodes and are labeled by the authors' last name and first initials. The larger the node, the more publications. The darker the node, the more the co-authors. Black nodes refer to 50 or more co-authors, while white nodes refer to less than 10 co-authors. Edges represent co-authorship relations. The width of an edge represents the relative number of co-author relationships.

3.5. Paper citation networks

To analyze and communicate the paper-citation network, we imported the complete dataset (citations in the 20 publications that were not in the ISI database were entered manually) into *HistCite*TM (Garfield, 2004). The resulting graph for the complete dataset is given in Fig. 4. The graphs for each of the three domains are shown in Figs. 5–7. In all graphs, nodes represent highly cited papers and edges denote citation links. The nodes are sorted in time with older papers on the top and younger papers at the bottom.

Fig. 4 shows the papers that are cited at least 30 times within the whole database, and if one of these highly cited papers cites another highly cited paper, they are linked. The paper by Holling (1973) is the most cited (362 times). Papers from very different knowledge domains cite the paper by Holling (1973). Another major publication that is highly cited across disciplinary boundaries is by Burton et al. (1978).⁴ Interestingly, the knowledge domain resilience develops quite separately from the domains vulnerability and adaptation. Very few cross citations exist. Only Holling (1986) cited Burton et al. (1978), and a few

“vulnerability/adaptation” papers and books refer to major resilience publications.

We also generated citation networks for the separate knowledge domains (Figs. 5–7). For the knowledge domain resilience, we used a threshold of 20 citations, and this figure is similar to the left part in Fig. 4. In the earlier years of this knowledge domain, we see papers on non-linear ecosystem properties (Holling, 1973; May, 1977; Pimm, 1984). Since the late 1970s, a number of key application areas developed. Among them are the management of forest for insect outbreaks (Ludwig et al., 1978), rangeland management (Walker et al., 1981; Westoby et al., 1989; Laycock, 1991; Friedel, 1991), and the management of lakes (Carpenter et al., 1999). Holling (1986) was instrumental in bringing the concept to the human dimensions of environmental change, leading to major papers on ecosystem management (Walters and Holling, 1990; Holling and Meffe, 1996). Gunderson et al. (1995), Berkes and Folke (1998), Gunderson and Holling (2002), and Berkes et al. (2003) have focused on comparing case studies on various regional social-ecological systems to understand how systems can deal with change and disturbances. The network of major papers shows the development of theoretical ecosystem properties to current applications on social-ecological systems.

⁴We combined citations referring to the 1978 and 1993 editions.

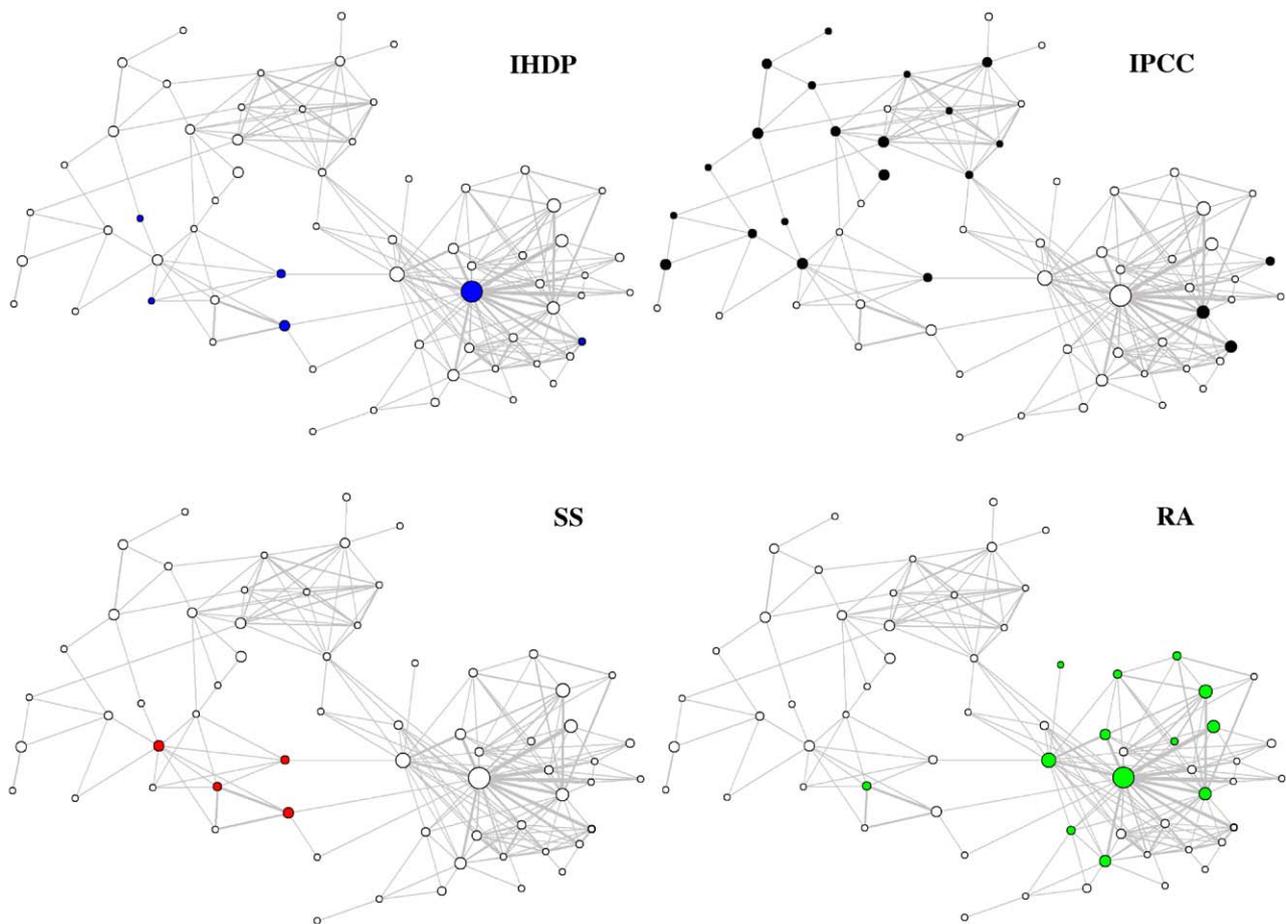


Fig. 3. Participation of scholars in different international networks using the spatial lay-out of the co-authorship network given in Fig. 2. IHDP, International Human Dimensions Programme on Global Environmental Change; IPCC, Intergovernmental Panel on Climate Change; SS, Sustainability Network; and RA, Resilience Alliance.

The knowledge domain vulnerability mapped using a threshold of 15 citations shows the centrality of [Burton et al.'s \(1978\)](#) research on the environment as a natural hazard. [Chambers \(1989\)](#) and [Swift \(1989\)](#) used the term vulnerability, but mainly in relation to poverty and development. [Liverman's \(1990\)](#) work connected the term vulnerability to global environmental change. A conceptual framework for vulnerability was introduced by [Blaikie et al. \(1994\)](#). Vulnerability research was increasingly influenced by research on climate change, which explains citation of the IPCC reports ([Watson et al., 1996, 1998](#); [McCarthy et al. 2001](#)). [Kates et al.'s \(2001\)](#) paper was on a recently formed network on sustainability science, which may affect the citation and co-authorship dynamics in this knowledge domain in the long run.

[Rappaport \(1967\)](#) was included as a seed for the adaptation knowledge domain, but it is not cited by other highly cited papers on adaptation. The geographer [Butzer \(1980\)](#) wrote a remarkable paper on adaptation to global environmental change, where he connected the insights from anthropology to the emerging literature on global environmental change. This anthropological perspective is

not directly connected with the dominant use of the term adaptation since the 1990s in the research on climate change. Since the 1990s, there is an increasing use of the term adaptation with regard to climatic change. [Rosenberg \(1992\)](#) published on adaptation of agriculture to climatic change. Most of the research on adaptation has focused on the agriculture sector, but since the late 1990s, the scope of sectors adapting to climate change was broadened, whereas remaining was climate change oriented ([Smithers and Smit, 1997](#); [Tol et al., 1998](#)).

An early synthesis of the concepts of resilience, vulnerability, and adaptation was made by [Timmerman \(1981\)](#), but this paper is not found to be a highly cited paper within the whole database. It is not cited among the highly cited papers on resilience. However, it is cited within the knowledge domains vulnerability and adaptation. Interestingly, it cites [Rappaport \(1977\)](#).

Next, we analyzed the complete paper citation networks to analyze if there is a general trend for papers to fall into multiple knowledge domains. By complete, we mean all the citations of papers in the database linked to any other paper in the database. The results are given in Fig. 8.

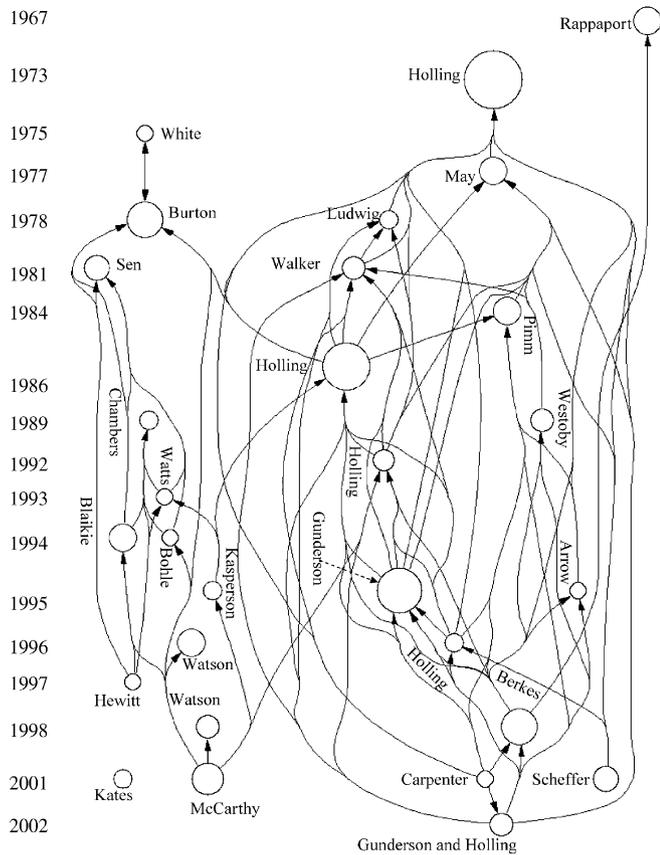


Fig. 4. Paper citation network of the most highly cited papers within the whole dataset (threshold 30 citations within the dataset). The node size denotes the number of citations, the arrows refer to citations (Carpenter et al., 2001; Holling, 1992).

About 20% of the papers published in the last five years can be categorized into two or three knowledge domains. One of the reasons for the increasing overlap might be the more complete coverage of abstracts in the ISI database since 1995. It appears that scholars more frequently use keywords from different knowledge domains or cite seminal papers from various knowledge domains. In sum, we are not able to provide a univocal explanation for the increased overlap.

When we analyze the cross citations between papers that are not members of the same knowledge domain, and relate this to the expected number of cross citations when papers would randomly cite other papers in this database, we see an increase of relative cross citations over time (Fig. 9). This is especially prevalent since 1995. However, this is still a preference for referring to papers within the same knowledge domain compared to the number expected when citing randomly. The main increase is caused by cross citations between papers on resilience and vulnerability. The increase in cross citations between papers on adaptation and vulnerability has been occurring for a longer period, perhaps since the late 1980s. Note that in this figure, we exclude citations of papers that are members of two knowledge domains.

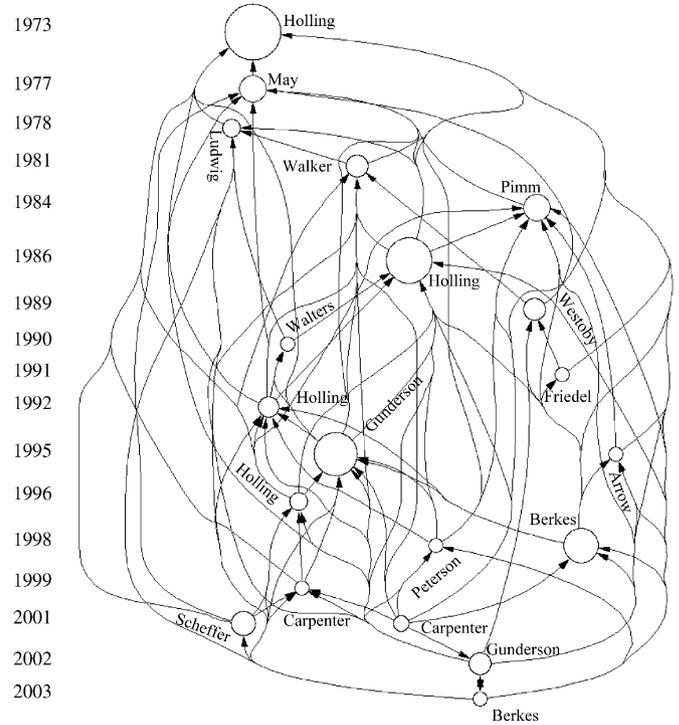


Fig. 5. Paper citation network of the most highly cited papers within the knowledge domain resilience (threshold 20 citations within the dataset). The node size denotes the number of citations, the arrows refer to citations (Carpenter et al., 2001; Holling, 1992; Peterson et al., 1998).

4. Discussion

The analysis of the publications related to resilience, vulnerability and adaptation of HDGEC shows that this research area experienced a major and still continuing increase in the number of published papers. It also shows that there are few interlinkages among the three knowledge domains, especially between resilience and vulnerability/adaptation.

The knowledge domain resilience is dominated by scholars related to the Beijer International Institute of Ecological Economics and RA. This knowledge domain has a number of very productive scholars who frequently cite each other's work. The knowledge domains of vulnerability and adaptation overlap and have similar dynamics. There is no theory or organizing framework that was the seed for the development of these two domains. The research on human-induced climatic change and the changing vulnerabilities and unavoidable necessities for adaptation stimulated the development of the research in the knowledge domains vulnerability and adaptation. This is reflected in the positions of the members of IPCC in the co-authorship network. It is remarkable that major publications on the knowledge domain resilience do not cite the other two knowledge domains vulnerability and adaptation, and the other way round. This observation reflects the historical developments of these domains.

We received a lot of interesting feedback on earlier drafts of this manuscript when it was circulated in academic

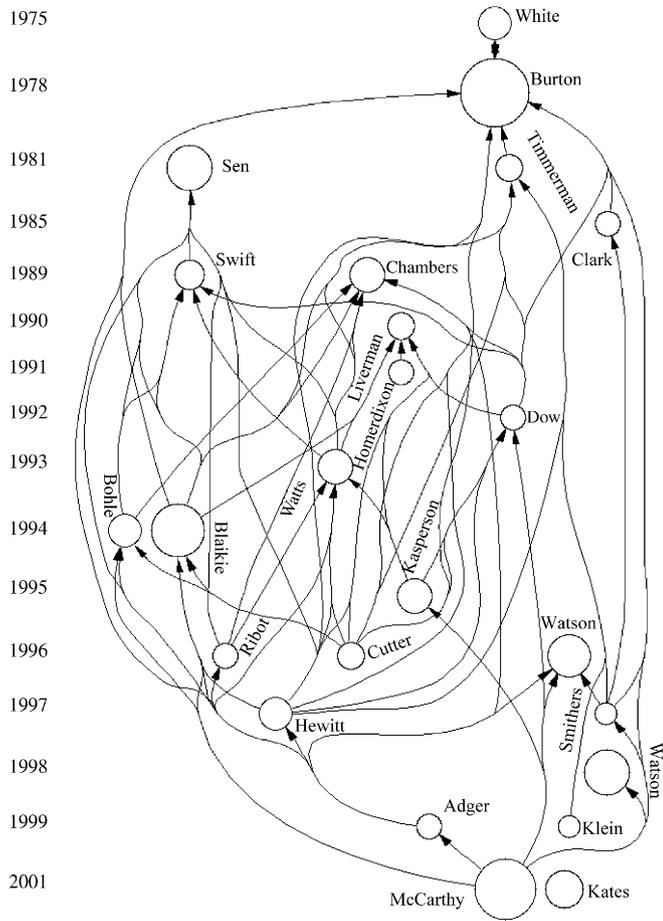


Fig. 6. Paper citation network of the most highly cited papers within the knowledge domain vulnerability (threshold 15 citations within the dataset). The node size denotes the number of citations, the arrows refer to citations.

circles. It is tempting to make statements on the past, present and future of the interdisciplinary research of human dimensions of global change. The nature of this analysis is to provide statistical information of a large dataset, not to make conclusions of individual occurrences. Our analyses do, however, raise certain questions that might be subject for future studies, like “what is the effect of international networks on co-authorship relations and on the diffusion of concepts?” “What are the disciplinary biases and bottlenecks in co-authorship networks in an interdisciplinary field like human dimensions of global environmental change?” These, and other interesting questions, might be useful for future research. From our analysis however, we see a trend of increasing overlap of domains and increasing cross citations. This suggests that an integration of the different knowledge domains into an overarching knowledge domain is looming.

Acknowledgements

This paper is part of a larger effort to analyze the cross-cutting theme of resilience, vulnerability and adaptation for

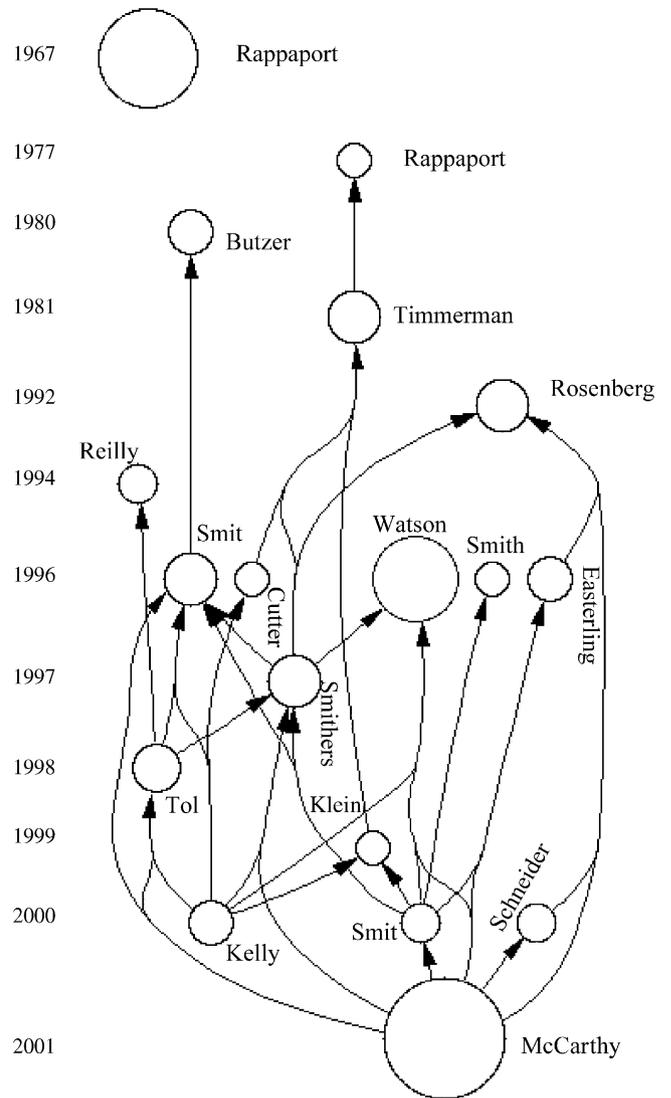


Fig. 7. Paper citation network of the most highly cited papers within the knowledge domain of adaptation (threshold 10 citations with the dataset). The node size denotes the number of citations, the arrows refer to citations (Kelly and Adger, 2000; Reilly et al., 1994; Schneider et al., 2000; Smith and Lenhart, 1996).

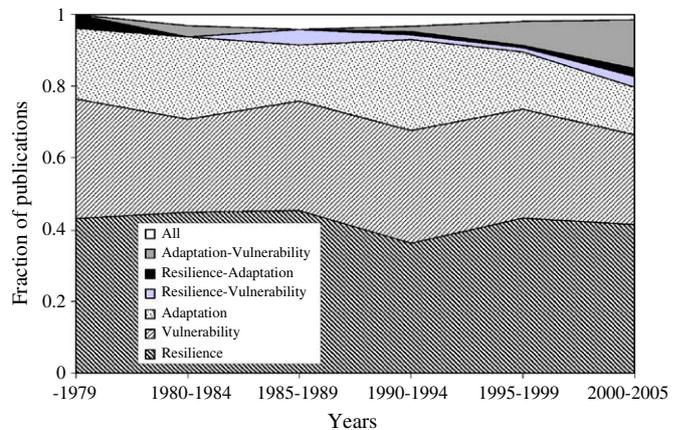


Fig. 8. Relative numbers of publication for the different knowledge domains for six five-year periods.

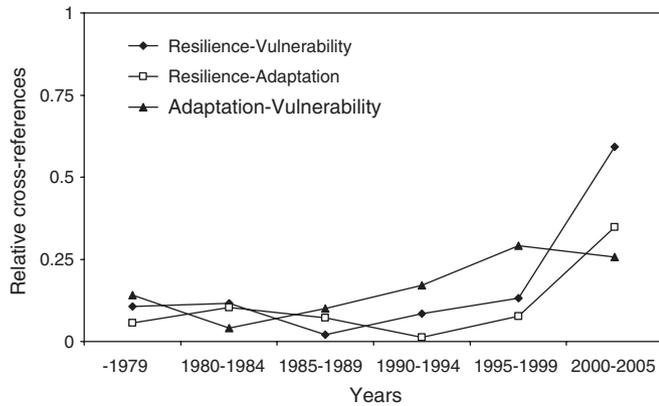


Fig. 9. Citations between distinct knowledge domains as a fraction of the total number of cross citations if citations were made randomly. This is done for six five-year periods.

the study on HDGEC, by a committee chaired by Lin Ostrom. We thank Neil Adger, Marty Anderies, Bill Clark, Carl Folke, Gilberto Gallopin, Roger Kasperson, Emilio Moran, Lin Ostrom, and Oran Young for providing suggestions on relevant literature and providing feedback on earlier versions of this paper. We acknowledge financial support from the IHDP and the National Science Foundation CAREER grant under IIS-0238261 to Katy Börner.

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