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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 2,286 publications over the last 30 years are related in terms of co-authorship relations, and citation relations. The number of publications in the three knowledge domains increased rapidly during the last decade. 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, 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 on a merge of the different knowledge domains.

Introduction

In recent years the concepts[1] of *resilience*, *vulnerability* and *adaptation* have increasingly been used in the research on human dimensions of global environmental change. We are interested to identify the structure and dynamics of major fields contributing to the particular concepts within the research on human dimensions of global environmental change (HDGEC). The study of 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 Gunderson (2000), Cutter (2003), Smit (1999, 2000). Four other papers in this special issue of Global Environmental Change, discuss the theoretical and methodological developments of the concepts resilience, vulnerability and adaptation with regard to human dimensions on global environmental change (Folke, 2005; Adger, 2005; Smit, 2005), as well as their conceptual similarities and differences (Gallopin, 2005).

The concept of *resilience* has been 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 the concept had been used by ecologists in their analysis of population ecology, and in the study of managing ecosystems. As such, it is mathematically based and model-oriented. Since the late 1980s the concepts has increasingly been used in the analysis of human-environmental interactions. A number of scholars working on resilience of social-ecological systems have organized themselves since in 1999, forming the Resilience Alliance.

The concept of *vulnerability* has its roots in the study of 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"(Blaike 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 is no focus on mathematical models, but a focus on the comparative analysis of case studies.

Adaptation to environmental variability has been a focus of anthropology since the early 1900s. In the 1990s scholars began to use the term adaptation for the study of the consequences of human induced climatic change, without explicitly relating this back to the conceptal origins in anthropology. The Intergovernmental Panel on Climate Change defines adaptations as an "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

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

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 review of all major works on *resilience*, *vulnerability* and *adaptation* seems impossible due to the large amount of papers and books published in the last 30 years and the diversity of the scientific disciplines involved. Here we present a bibliometric analysis of the three knowledge domains 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, we are interested to objectively identify major knowledge domains, experts, papers, etc. in the three knowledge domains of interest. In addition, we would like to identify interconnections among and the import and export of research between the three knowledge domains.

The remainder of this paper presents the results of analyzing 2286 publications related to the study of *resilience*, *vulnerability* and *adaptation* over the last 30 years. 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 increasing flood of information and responding specialization) over time.

Data collection

Most research results in the domains of *resilience*, *vulnerability* and *adaptation* is published in journals. All three knowledge domain are rather young and a majority of work in these three areas was published over the last 30 years. Therefore, the *Arts and Humanities Index*, the *Social Science Citation Index* and the *Science Citation Index* as provided by the Institute of Scientific Information (ISI) was used to acquire the raw material for the bibliometric analysis. A manual check of ISI's journal coverage conformed that all relevant journals are covered.

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

Keyword-Based Search

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

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[2]	Social adaptability
	Environmental security[2]	Human adaptation
		Human adaptability
		Adaptive response
		Adaptive capacity
		Adaptive strategies
		Human biology[2]
		Adaptation & environment[2](only social science and humanity)
		Adaptability & environment[2] (only social science and humanity)

Cited Reference Search

A set of seminal papers, also called 'seeds', that 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 2: Seminal papers used to retrieve papers for the three knowledge domains based on cited reference search

Resilience	Vulnerability	Adaptation
Holling (1973, 1986)	White and Haas (1975)	Rappaport[2] (1968, 1976)
May (1977)	Burton et al. (1978)	Butzer (1980)
Ludwig et al. (1978)	Sen (1981)	Timmerman (1981)
Timmerman (1981)	Timmerman (1981)	Rosenberg (1992)
Walker et al. (1981)	Clark (1985)	Easterling (1996)
Pimm (1984)	Chambers (1989)	Smit et al. (1996, 2000)

[2] Add in the second round of information retrieval in March 2005.

Gunderson et al. (1995) Berkes and Folke (1998) Adger (2000) Scheffer et al. (2001) Gunderson and Holling (2002) Berkes et al. (2003)	Swift (1989) Dow (1992) Liverman (1990) Watts and Bohle (1993) Bohle et al. (1994) Blaikie et al. (1994) Kasperson et al., (1995) Cutter (1996) Ribot et al. (1996) Watson et al. (1996, 1998) Hewitt (1997) Adger (1999) Klein and Nicholls (1999) McCarthy et al. (2000) Kates et al. (2001)	Watson et al. (1996) Smithers and Smit (1997) Smit et al. (1999) Tol et al. (1998) McCarthy et al. (2001)

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

Data Cleaning

The title, keywords and abstract of each document retrieved by keyword based and cited reference search was checked manually by two independent experts. Only publications in the area of human dimensions of environmental change were kept. Studies which focused exclusively on ecological dynamics (resilience of plankton communities, for example) or on social dynamics (such as adaptation of organizations) were excluded. 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 into an MS Access database for further data cleaning such elimination of duplicate records and unification of 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

Discussion of the Data Set

The acquired dataset has a number of potential shortcomings. It mostly covers journal papers. Relevant books and book chapters might have been missed as they are not included in the ISI database. This might introduce biases 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, have been used in various ways, often unrelated to the study of human dimensions of global environmental change. 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 human dimensions of global environmental change.

Data Analysis and Visualization

General Statistics

The final dataset contains 2,266 unique journal papers and 20 books and other non-journal paper published between 1967-2005. From those, 1,084 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 contributions to more than one knowledge domain.

Figure 1 shows the number of papers in the three knowledge domains over the last 30 years. 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 paper data shows a linear increase of papers over time (Boyack and Bäcker, 2004). A potential explanation is the increased interest in global environmental change, especially human induced climatic change around the same time. The creation of various institutions and networks such as IHDP, the Resilience Network/Alliance, the Sustainability Science group (organized in 2000/2001), the Beijer Institute for Ecological Economics (organized in 1991), and other research groups also served to increase the amount of research conducted within the knowledge domains.

[Figure 1]

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 over the last 30 years. This might be a consequence of more collaboration, for example, via international interdisciplinary networks. This trend is similar for all three knowledge domains.

Journal Statistics

If we exclude the 20 books and other non-journal publication, we have 2266 papers, which have been published in about 568 different journals. This shows a very 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, Ecosystems) were created after 1990.

Table 3 (right) shows citation counts per journal compiled using the *HistCite*™[3] 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* due to the publications citing the key paper in the field Holling (1973). Compared to the number of papers it is remarkable that *Ecological Economics* and *Environmental Management* are not among the highly cited journals. Publications in *Science* and *Nature* are highly cited and this is reflected in the ranking as well.

Table 3: The 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	#articles	Journal	# citations
1	Climatic Change	96	Ann. Review Ecology	400
2	Global Environmental Change	74	Climatic Change	334
3	Climate Research	62	Nature	289
4	Ecological Economics	58	Global Env. Change	258
5	Environmental Management	57	Ecosystems	199
6	Ambio	50	Science	158
7	Ecological Applications	34	Journal of Range. Manag.	135
8	Human Ecology	31	Ecological Applications	132
	Conservation Ecology	30	Ambio	123
10	Ecosystems, Env Monitoring and Assessment	29	Progress in Human Geog.	94

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

Table 4: The top 10 journals with the largest number of papers in resilience, vulnerability and adaptation over the period 1977-2005. (The # sign refers to the number of papers).

	Resilience		Vulnerability		Adaptation	
	Journal	#	Journal	#	Journal	#
1	Ecological Economics	57	Climatic Change	61	Climatic Change	57
2	Env. Man.	44	Global Env Change	52	Global Env Change	44
3	Ambio	37	Climate Research	46	Climate Research	34
4	Ecological Applications	31	AAAG	23	American Anthropology	15
5	Conservation Ecology	28	Disasters	23	Human Ecology	14
6	Ecosystems	28	Water Air and Soil Pol	17	Env Mon & Ass	12
7	Ecological Modelling	21	Ambio	16	Climate Policy	12
8	Conservation Biology	16	Env Monitoring & Ass	16	Building Research	9

[3] We used HistCite Version: 2004.11.12

9	Forest Ecology and Man.	16	Ocean & Coastal Man	14	Ecological Economics	9
10	Journal of Env. Man.	15	Natural Hazards, Climate Policy	13	IDS Bulletin, Current	8
				13	Anthro, Water Air & Soil Pol	8
						8

Using *HistCite*™ 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).

Table 5: The top 10 journals with the largest number of citations in resilience, vulnerability and adaptation over the period 1977-2005. (The # sign refers to the number of received citations).

	Resilience		Vulnerability		Adaptation	
	journal	#	journal	#	Journal	#
1	Ann Review Ecology	398	Global Env Change	154	Climatic Change	189
2	Nature	263	Climatic Change	152	Global Env Change	113
3	Ecosystems	180	Prog in Hum Geog	80	Climatic Research	28
4	J. of Range Manag.	130	IDS Bulletin	74	Agr. and Forest Meteo	24
5	Ecological Appl.	114	Science	53	Prog. in Hum Geog.	19
6	Ambio	94	AAAG	50	Building Research & Info	17
7	Science	80	Climate Research	37	Prof. Geographer	15
8	Journal of Ecology	66	World Development	34	Ambio	14
9	Ecological Economics	64	Ambio	25	Env Mon & Ass	14
10	Conservation Biology	62	Geoforum, Disasters, Env Mon & Ass	23	Nature / American Anthro	12

Author Statistics

Next, we were interested in analyzing the most productive and most collaborative authors within our database (including the 20 publications we excluded in the journal analysis). Table 6 shows the top 10 authors who have been 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. Using *HistCite*™ to calculate the number of times authors are cited, C.S. Holling, currently emeritus Professor at the University of Florida, and before at British Columbia University (Canada) and the International Institute for Applied Systems Analysis (Austria), is by far the most cited author, followed by Folke.

Table 6: Top authors of the complete data set. 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 times cited.

	Number of publications		Number of times cited	
	Author	# Publications	Author	# Citations
1	C. Folke	50	C.S. Holling	1,280
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

Table 7 presents the most productive institutions and countries. Papers are allocated to institutions and countries based on the affiliations of the first author. The most successful 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. Interestingly, small countries such as the Netherlands and Sweden, do much better than larger non-native English speaking countries like Germany and France, where scholars may publish more frequently in non-English journals that are less frequently included in the ISI Web of Knowledge.

Table 7: The top 10 highly productive institutions (left) and countries (right). The publications are allocated to the institutions and countries of the lead author. For 91 publications this information was not available.

	Number of publications		Number of publication	
	Institution	# Publications	Country	# Publications
1	Stockholm University	69	USA	1045
2	Wisconsin University	60	UK	282
3	CSIRO	58	Canada	272
4	Univ of East Anglia	53	Australia	152
5	Univ of British Colombia	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

Using *HistCite*™, highly cited papers that are not part of our database were identified. These are Holling (1978) with 135 citations, Walters (1986) with 121, Ostrom (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 et al. (1997) with 55, Rosenzweig et al. (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.

Co-Author Networks

Next, we were interested to understand the scholarly interactions and the structure of the research community based on co-authorship relations. A total of 3,860 unique 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, co-author networks can be analyzed and visualized.

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 9 authors that 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 keep only those 67 authors that had a minimum of 5 papers. The thresholds were manually selected such that the number of authors and their co-authorships was sufficiently large to derive meaningful structures.

The resulting network was laid out using the Pajek (Batagelj and Mrvar, 1997) network visualization package, see Figure 2. The most densely linked group of authors around the Folke node publishes in the domain of *resilience*. The other knowledge domains are more dispersed. On of the reasons for the dense connections might be the activities of the *Beijer Institute for Ecological Economics* and the *Resilience Alliance* who have brought many authors together.

[Figure 2]

Next, we analyzed the participation of authors in various international research networks like *International Human Dimensions Programme on Global Environmental Change* (IHDP), *Intergovernmental Panel on Climatic Change* (IPCC), *Sustainability Science* (SS) and *Resilience Alliance* (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 Resilience Alliance in 2004, or is listed in the research group on Sustainability Science see http://sust.harvard.edu/people.htm (accessed on January 12, 2005).

Figure 3 shows four networks that have the identical layout shown in Figure 2 but that are color coded according to the author's participation 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.

[Figure 3]

We see that Resilience Alliance and Sustainability Science, 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 see also

clusters in those networks. The figure suggests that international networks stimulate co-authorship networks.

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*™ (Garfield, 2004). The resulting graph for the complete data set is given in Figure 4. The graphs for each of the three domains are shown in Figure 5-7. In all graphs, nodes represent highly cited papers and edges denote citation links. The nodes are sorted in time with old papers on the top and young papers at the bottom.

Figure 4 shows papers which are cited at least 30 times within the whole database, and if one of these highly papers cites another highly cited paper, they are linked. Holling (1973) is the most cited paper (362 times). Papers from very different knowledge domains cite Holling (1973). Another major publlication that is highly cited across disciplinary boundaries is Burton et al. (1978)[4]. Interestingly, the knowledge domain *resilience* develops quite separately from the knowledge domains vulnerability and adaptation. Very few cross citations exist. Only Holling (1986) cited Burton et al.'s (1978) and a few "vulnerability/adaptation" papers and books refer to major resilience publications.

[Figure 4]

We also generated citation networks for the separate knowledge domains (Figures 5-7). For the knowledge domain resilience we used a threshold of 20 citations, and this figure is similar to the left part of Figure 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 to bring 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 of 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 to social-ecological systems.

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) use the term vulnerability, but mainly in relation to poverty and development. Liverman's work connects the term vulnerability to global environmental change. A conceptual framework for vulnerability has been introduced in Blaikie et al. (1994). The vulnerability research got increasingly influenced by impacts of climate change which explains the occurrence of the IPCC reports (Watson et al., 1996; 1998 and McCarthy, 2001). Kates et al. (2001) is a paper of a recently

[4] Note that we combined citations referring to the 1978 and 1993 editions.

formed network on sustainability science, which may affect the citation and coauthorship dynamics in this knowledge domain in the long run.

Rappaport (1967) was recommended to be included as a seed for the adaptation knowledge domain, but it is not cited by the 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 climate change research. 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 adaptation research has focused on the sector agriculture, but since the late 1990s the scope of sectors adapting to climate change has been broadened, but still climate change oriented (e.g. Smithers and Smit, 1997; Tol et al., 1998).

It might be interesting to point to the remarkable paper of Timmerman (1981) that appears to have been an intellectual forerunner for much of the current research combining the concepts of *resilience*, *vulnerability*, and *adaptation*. Timmerman (1981) does not appear in the highly cited papers within the whole database. It is not cited among the highly cited papers in *resilience*, but is in the knowledge domains *vulnerability* and *adaptation*. It also cites Rappaport (1977).

[Figure 5]
[Figure 6]
[Figure 7]

Next, we used a threshold of zero to identify the complete paper citation network using HistCite™. The result was converted it into Pajek format. The 330 papers that were not cited or did not cite any paper in the whole database were excluded. The final paper citation network contains 1,956 papers.

The Fruchterman and Reingold (1991) layout algorithm was applied to generate the map shown in Figure 8. Paper nodes were color coded according to their knowledge domain. When papers are categorized into two knowledge domains, the colors of the inner circle and the border differ. When a paper falls into all three knowledge domains, it is given in yellow.

The Figure shows that papers cluster according to their topics. That is papers on resilience are much more likely to cite other resilience papers than they are to cite research from other domains. Resilience papers are strongly clustered. The knowledge domains vulnerability and adaptation are weakly interlinked.

[Figure 8]

Next, we analyzed the complete paper-citation networks (see Figure 8) to analyze if there is a general trend for papers to fall into multiple knowledge domains. The results are given in Figure 9. About 20% of the papers published in the last five years can be categorized into two or three knowledge domains. One of the reasons of 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.

When we analyze the cross-citations between papers that are not members of the same knowledge domain, we see a sharp increase from 3% to 13% in the number of citations since the mid 1980s. The main increase is caused by cross citations between "resilience" and "vulnerability". This includes citations between any paper in one knowledge domain, and any other paper in the other two knowledge domains. In Figure 10, the percentage of inter-citations is given for the three knowledge domains. Note that we exclude in this figure citations of papers which are members of two knowledge domains.

[Figure 9]

[Figure 10]

Discussion

The analysis of the publications related to resilience, vulnerability and adaptation of human dimensions of global environmental change 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 Institute of Ecological Economics and the Resilience Alliance. This knowledge domain has a number of very productive scholars who cite each others work. The knowledge domains vulnerability and adaptation overlap and have similar dynamics. There is no theory or organizing framework which has been the seed for the development of these two domains. Given the high presence of scholars related to the IPCC, 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. It is remarkable that there is such a low frequency of citations between the knowledge domain resilience and the other two knowledge domains vulnerability and adaptation. This observation reflects the historical developments. However, in recent years scholars from different knowledge domains start to use similar keywords and cross cite each others work more frequently. This suggest a merge of the different knowledge domains is looming.

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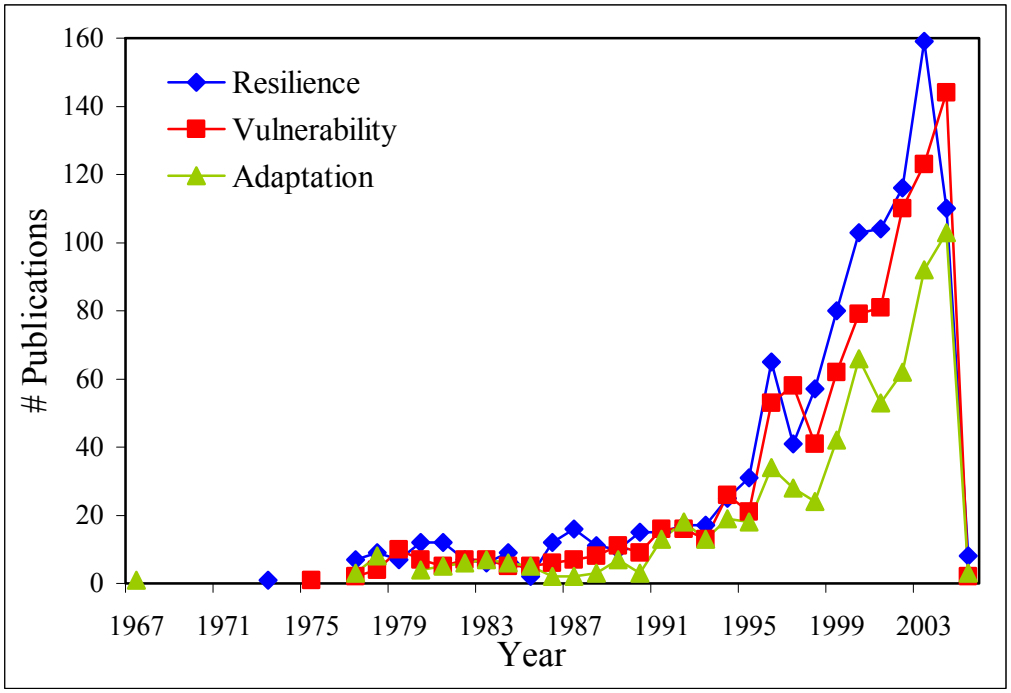

Figure 1: Number of papers published in the three knowledge domains per year. Data for 2004 and 2005 is incomplete.

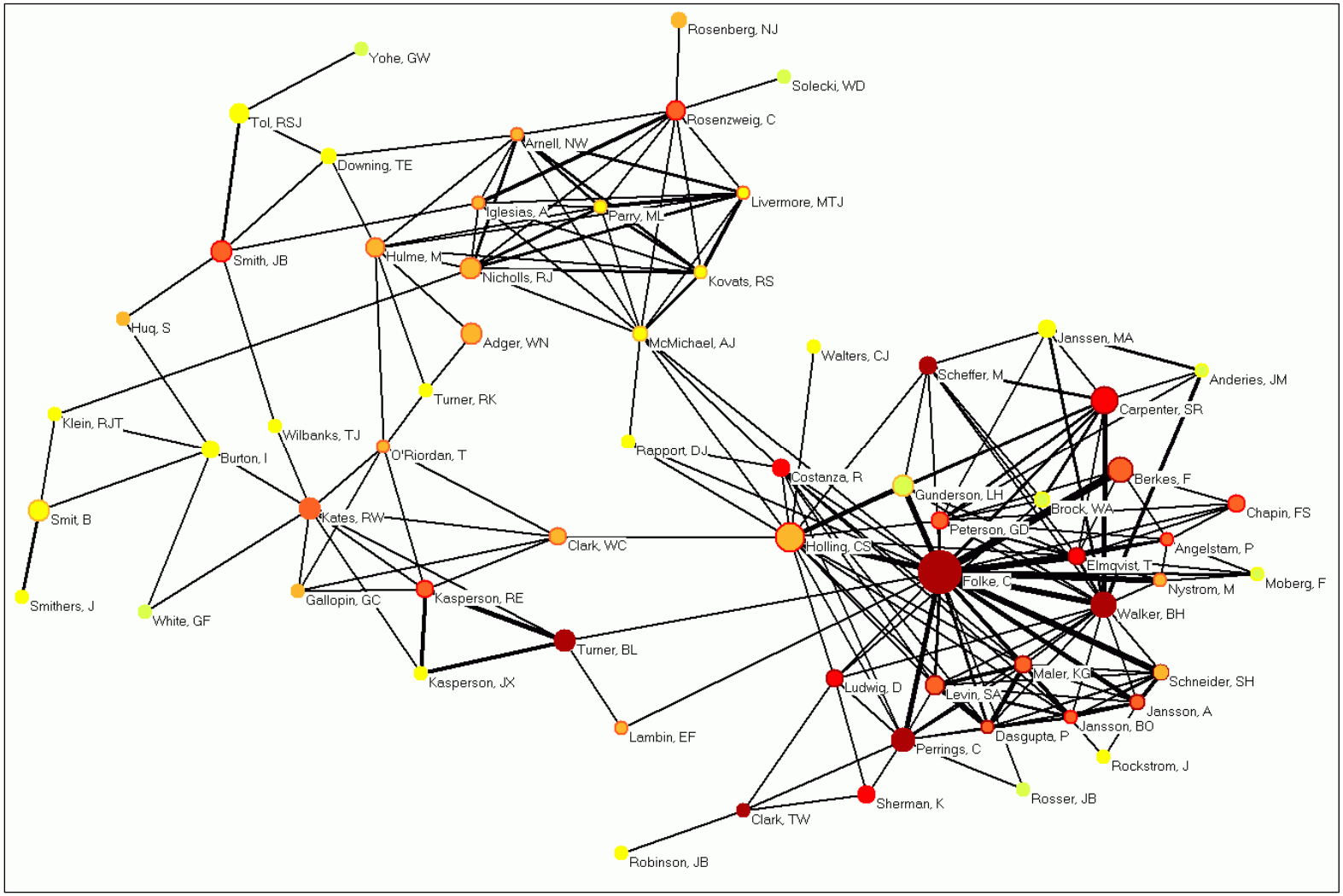

Figure 2: Co-author network of most productive and best connected authors with the strongest co-authorship relations. Circles denote author nodes and are labeled by the authors last name and first initials. Edges represent co-authorship relations.
Legend:
Node – author
Node area size - # of publications.
Node area color - # of unique co-authors
Node edge color - # of co-authorships.

- 1-9
- 10-19
- 20-29
- 30-39
- 40-49
- 50 or more

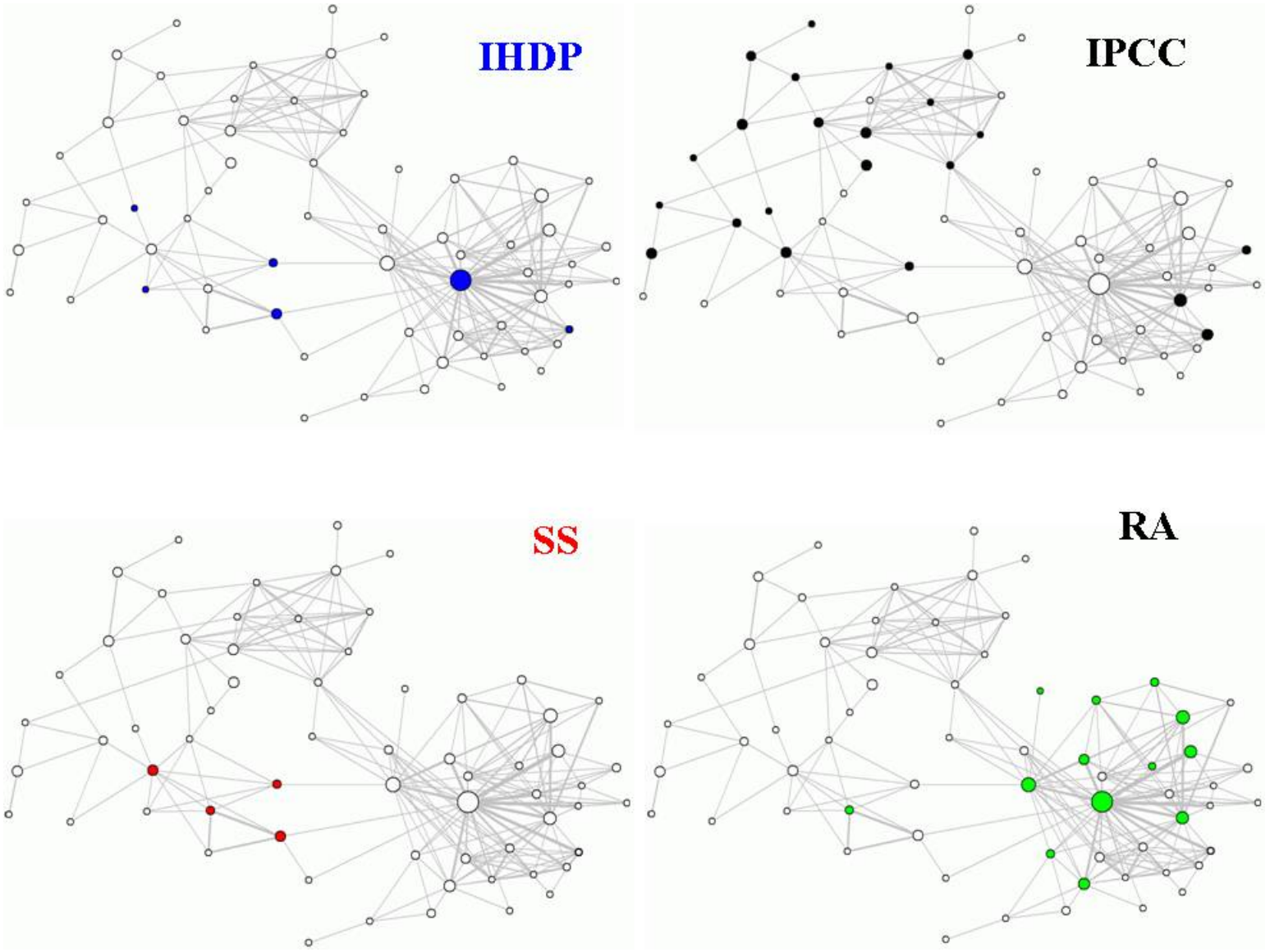

Figure 3: Participation of scholars in different international networks using the spatial lay-out of co-authorship network given in Figure 2. IHDP is the International Human Dimensions Programme on Global Environmental Change, IPCC is the Intergovernmental Panel on Climate Change, SS is the Sustainability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

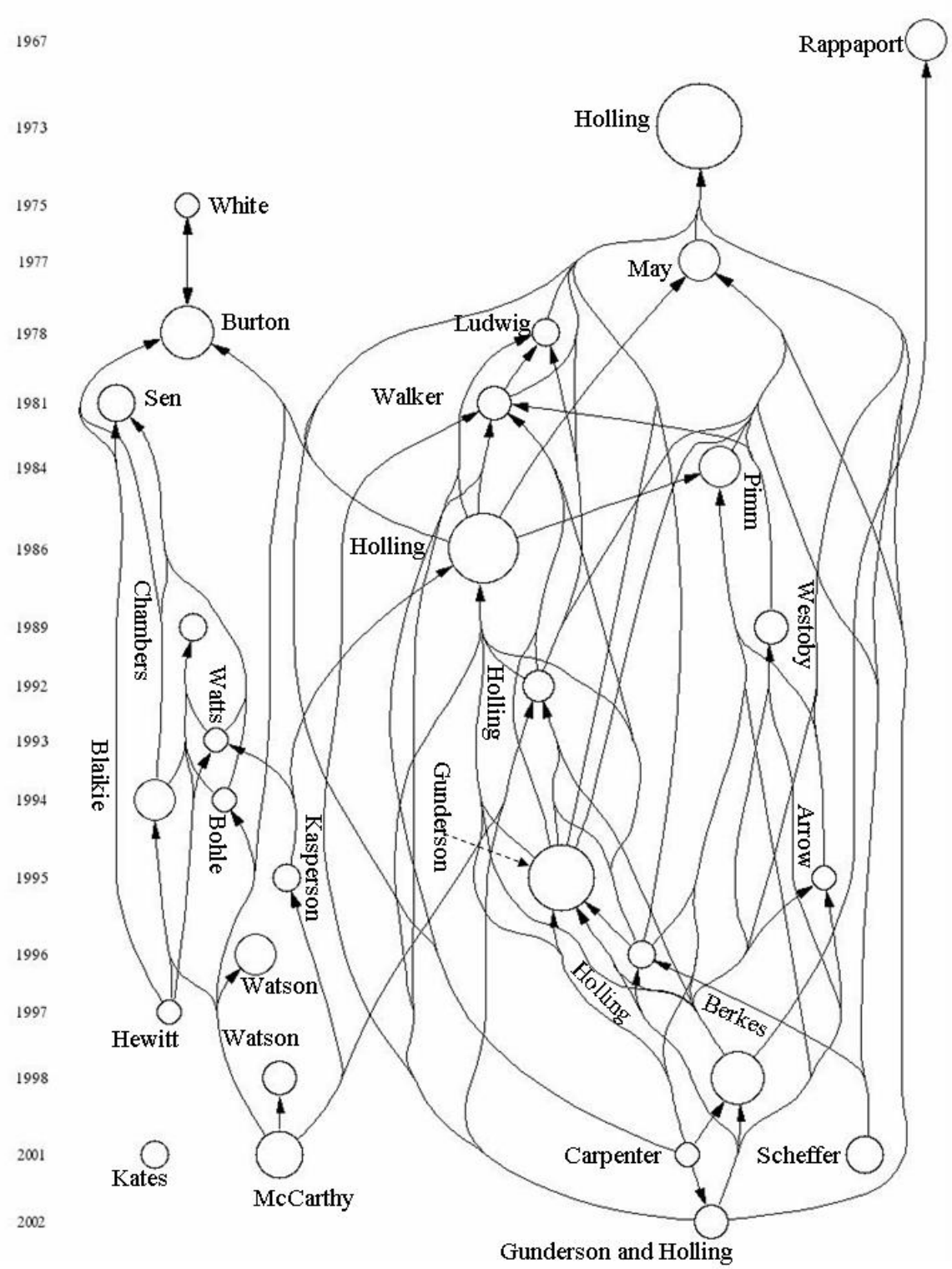

Figure 4: Paper citation network of the most highly cited papers within the whole database (Threshold 30 citations within the database). The node size denotes the number of citations.

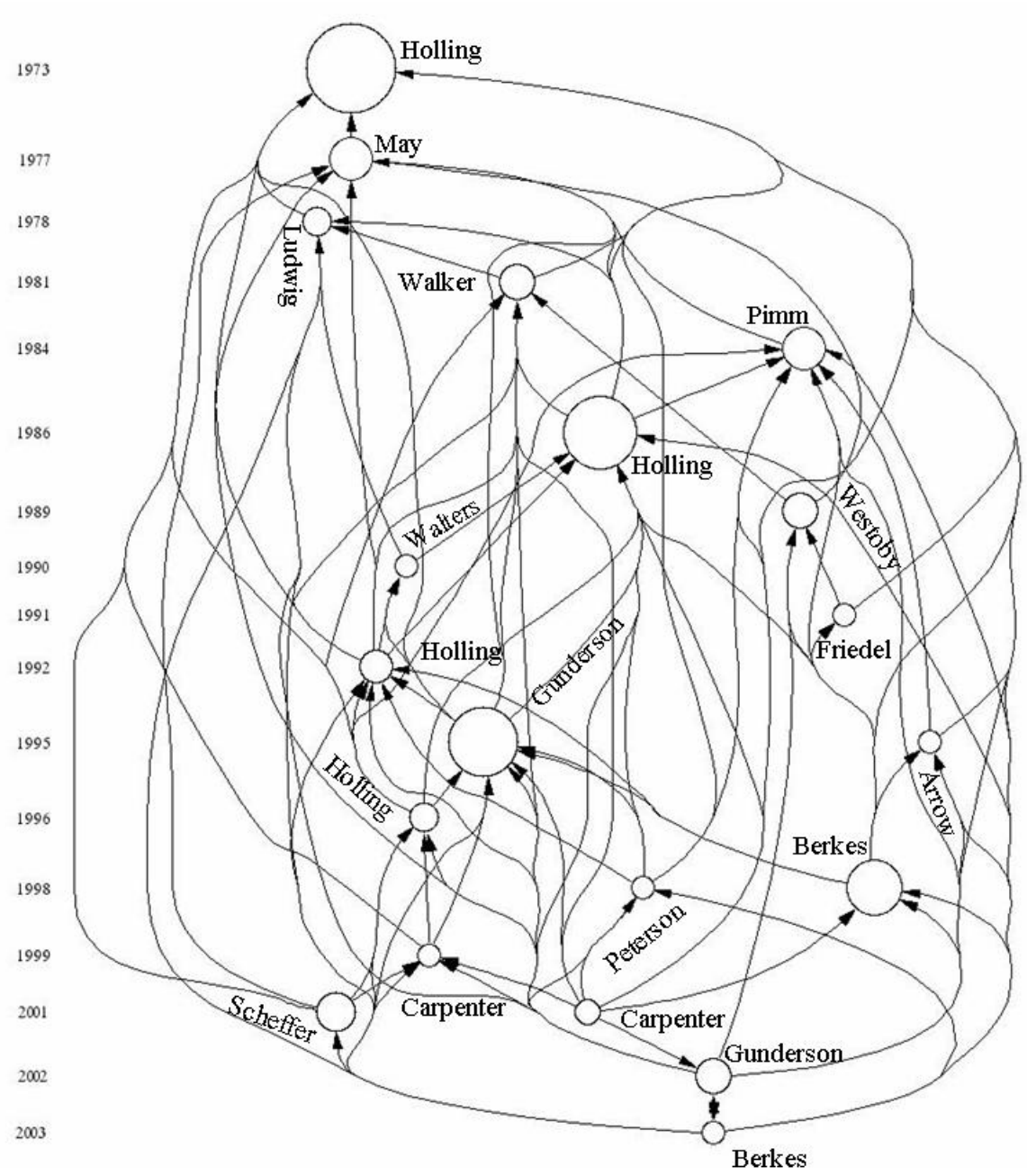

Figure 5: Paper citation network of the most highly cited papers within the knowledge domain resilience (Threshold 20 citations within the database). The node size denotes the number of citations.

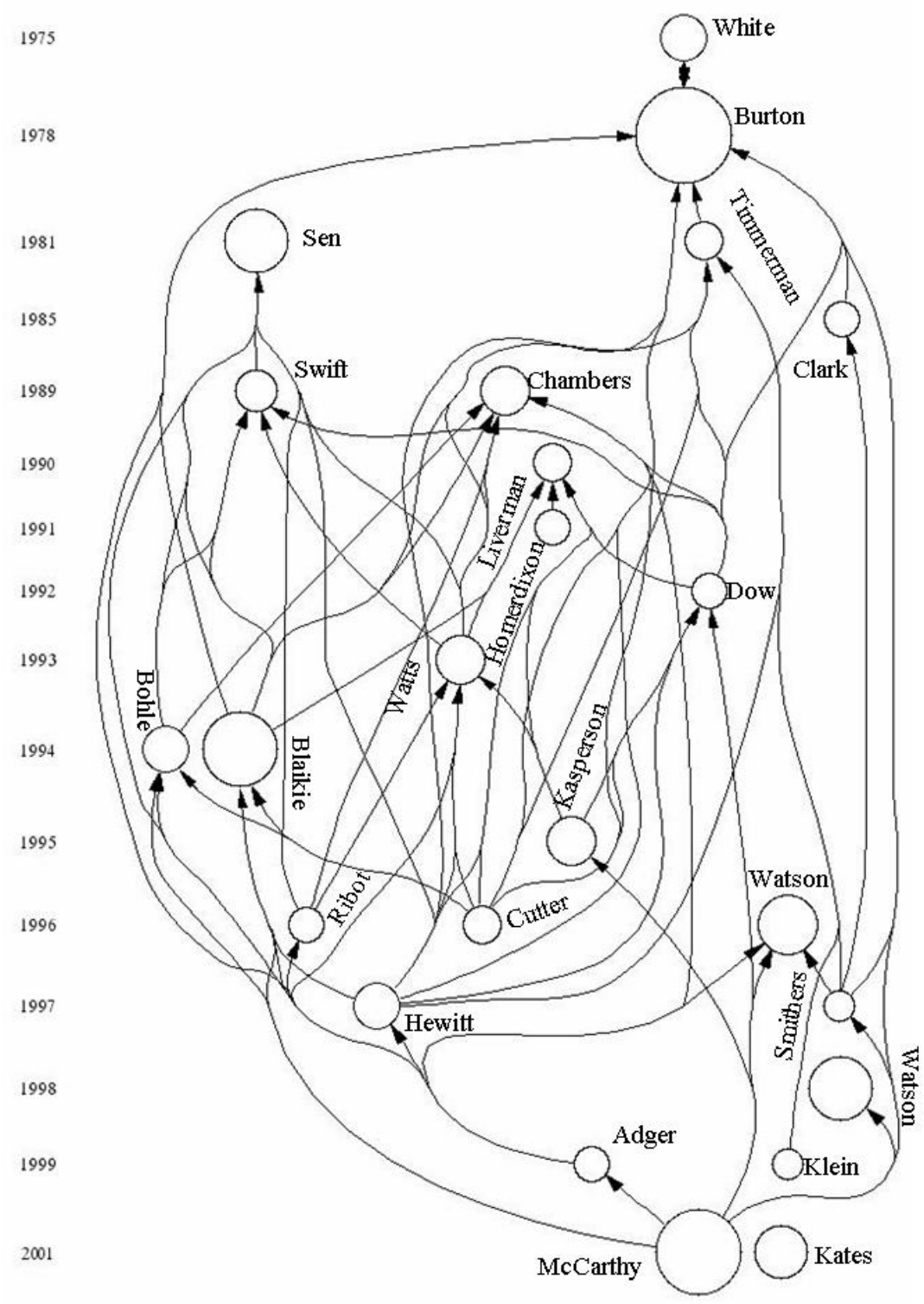

Figure 6: Paper citation network of the most highly cited papers within the knowledge domain vulnerability (Threshold 15 citations within the database). The node size denotes the number of citations.

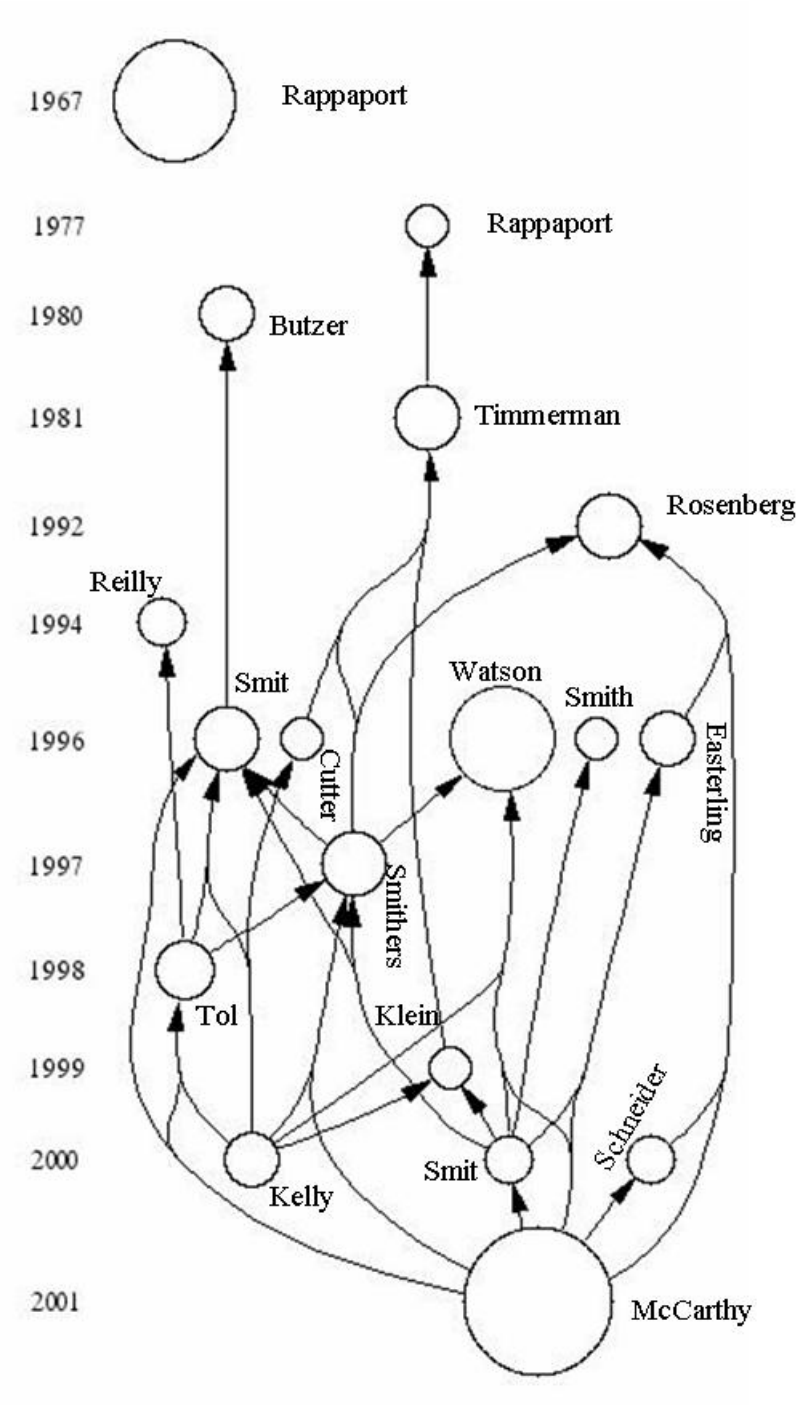

Figure 7: Paper citation network of the most highly cited papers within the knowledge domain of adaptation (Threshold 10 citations with the database). The node size denotes the number of citations.

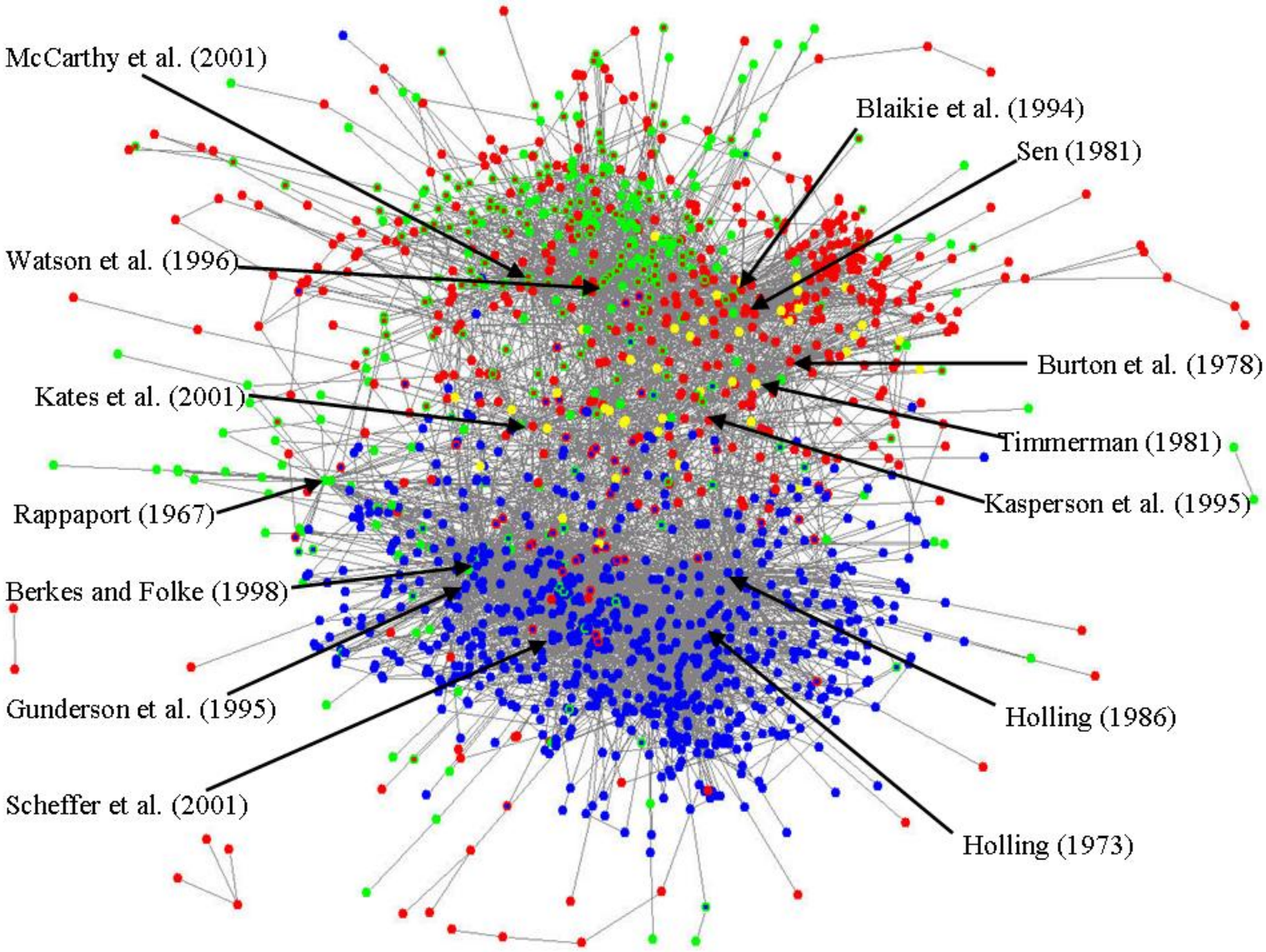

Figure 8: Paper citation network of 1956 papers. Blue refers to resilience, red to vulnerability, and green to adaptation. When papers are within two knowledge domains, the colors of the inner circle and the border differ. When a paper is categorized into all three knowledge domains, it is yellow.

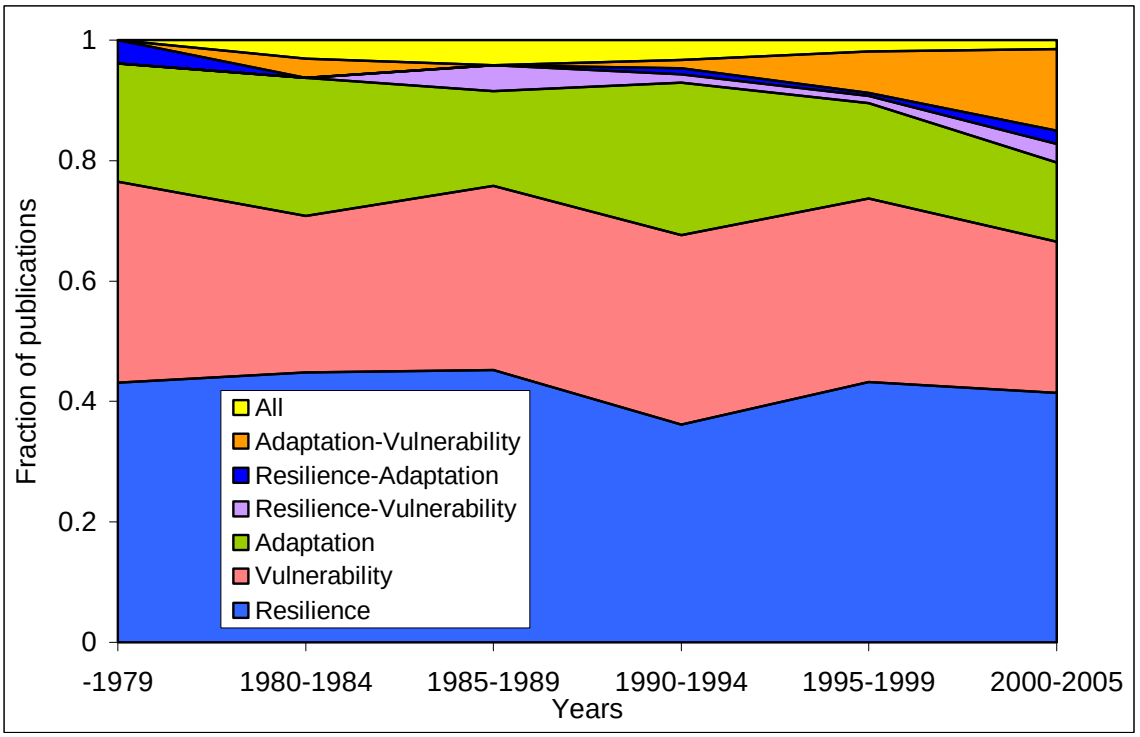

Figure 9: Relative number of publication for the different knowledge domains for six five year periods.

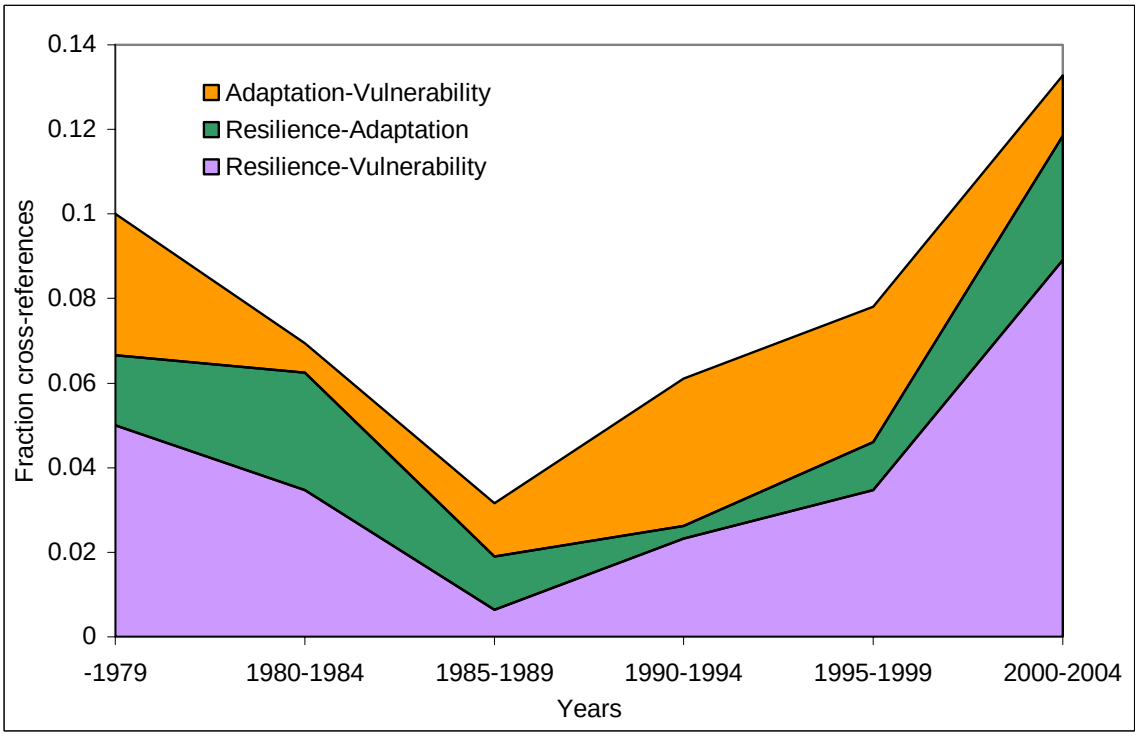

Figure 10: Citations between distinct knowledge domains as fraction of the total number of citations for six five-year periods.