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Review Article

Resilience of Complex Systems: State of the Art and Directions for Future Research

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This paper reviews the state of the art on the resilience of complex systems by embracing different research areas and using bibliometric tools. The aim is to identify the main intellectual communities and leading scholars and to synthesize key knowledge of each research area. We also carry out a comparison across the research areas, aimed at analyzing how resilience is approached in any field, how the topic evolved starting from the ecological field of study, and the level of cross-fertilization among domains. Our analysis shows that resilience of complex systems is a multidisciplinary concept, which is particularly important in the fields of environmental science, ecology, and engineering. Areas of recent and increasing interest are also operation research, management science, business, and computer science. Except for environmental science and ecology, research is fragmented and carried out by isolated research groups. Integration is not only limited inside each field but also between research areas. In particular, we trace the citation links between different research areas and find a very limited number, revealing a scarce cross-fertilization among domains. We conclude by providing some directions for future research.

1. Introduction

A common property of many complex systems is resilience, that is, the ability of the system to react to perturbations, internal failures, and environmental events by absorbing the disturbance and/or reorganizing to maintain its functions.

The word *resilience* originated in the 17th century from the Latin term "*resiliere*," which means to jump back. In academic literature, the concept emerged in the 1970s from ecology studies on interacting populations, such as predators and prey, and their functional responses. According to Holling's seminal study, "*resilience determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist*" [1]. Early studies, according to which the system "bounces" back to the equilibrium state predisturbance, related resilience to stability and the capacity to absorb environmental shocks and still maintain function. Successively, the concept was enriched to include the ability of the system to face with and adapt to change. This proactive perspective focuses on the complex system features and their capacity for renewal, reorganization, and growth [2–4]. In such a view, resilience is a multifaceted capability of complex systems that encompasses avoiding, absorbing, adapting to, and recovering from disruptions [5]. It involves the following main complex system features: self-organization, adaptive capacity, and absorptive capacity.

Since then, over the last 40 years, the topic of resilience has grown a lot in popularity. Applications have spread into multiple domains such as ecology, environmental science, management, economics, engineering, computer science, and psychology. Thus, today, resilience is a multidisciplinary topic spanning natural science, social sciences, and engineering [6–9]. Studies on resilience concern a great variety of complex systems embracing individuals, ecosystems, organizations, communities, supply chains, computer networks, and building infrastructures, just to name a few of the most popular ones. In the literature, resilience can be subclassified as ecological resilience, organizational resilience, resilience engineering, system resilience, and psychological resilience.

Table 1: Definitions of resilience in different domains.

	Definitions	Sources
Ecological resilience	Measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables.	[1]
	Ability of a social-ecological system to absorb disturbances and reorganize while undergoing change, so as to still retain essentially the same functions, structures, identity, and feedbacks.	[3]
	The magnitude of disturbance that can be absorbed before the system changes its structure by changing the variables and processes that control behavior.	[10]
	The ability of the system to maintain its identity in the face of internal change and external shocks and disturbances.	[8]
	Measure of the amount of change needed to change an ecosystem from one set of processes and structures to a different set of processes and structures.	[11]
Organizational resilience	Ability to bounce back from a disruption.	[12]
	Ability to return to the original state or to a new, more desirable one, after experiencing a disturbance.	[7]
	Capability to face disruptions and unexpected events in advance, thanks to the strategic awareness and a linked operational management of internal and external shocks.	[6]
Resilience engineering	Ability of a system to sense, recognize, adapt, and absorb variations, changes, disturbances, disruptions, and surprises.	[13]
	The ability to bounce back when hit with unexpected events.	[14]
	The joint ability of a system to resist (prevent and withstand) any possible hazards, absorb the initial damage, and recover to normal operation.	[15]
Economic resilience	Inherent ability and adaptive response that enable firms and regions to avoid maximum potential losses.	[16]
	Capacity to reconfigure, that is, to adapt its structure (firms, industries technologies, and institutions) so as to maintain an acceptable growth path in output, employment, and wealth over time.	[17]
Psychological resilience	Those factors that modify, ameliorate, or alter a person's response to some environmental hazard that predisposes to a maladaptive outcome.	[18]
	The process of, capacity for, or outcomes of successful adaptation despite challenging or threatening circumstances.	[19]
	The personal qualities that enable one to thrive in the face of adversity.	[20]
	The capacity of individuals to cope successfully with significant change, adversity, or risk.	[21]

A selection of definitions of resilience for each subclass is provided in Table 1.

This great variety of definitions and applications calls for a systematic analysis aimed at clarifying the main aspects of each research domain. This is useful to identify the origin of the concept, to trace its development, and to clarify the peculiarities of each domain as well as the common trends.

Thus, we conduct a systematic literature review of resilience of complex systems covering various disciplines: environmental science, ecology, operation research, management science, engineering, computer science, economics, and psychology. In doing so, we use in combination bibliometric techniques and qualitative analyses of the literature. In particular, we use bibliometric techniques to identify intellectual communities, the most influential scholars, and the most influential papers in each field. Furthermore, we synthesize key knowledge of different research fields by answering the following questions:

(1) Which are the complex systems of interest *(complex systems)*?

(2) Which types of disturbance affect the system *(disturbances)*?

(3) Which are the main dimensions of resilience *(dimensions)*?

(4) Which are the main attributes of the system affecting resilience *(attributes)*?

In fact, as recently argued by Helfgott [22], to clarify the resilience concept and identify its main building blocks, it is essential to take into account resilience "of what" and "to what." Resilience "of what" includes the analysis of the boundaries of the complex system and of their features critical for resilience. Resilience "to what" concerns the characteristics of disturbance, specifying its nature and magnitude.

In addition, we also carry out comparisons across research areas, in order to analyze how resilience is approached in the different fields, by distinguishing the research methodologies commonly adopted. We are also interested in identifying whether relationships between research areas exist which demonstrate the existence of cross-fertilization among domains. To this end, we build a citation network of the papers and analyze it.

Our study differs from previous ones on the topic. Firstly, we note that recent literature reviews on resilience, while recognizing its multidisciplinary nature and analyzing studies in different domains, are nonetheless conducted with the aim of giving insight only into a specific application context or research area. For example, Annarelli and Nonino [6] review papers on organizational resilience with specific emphasis on the development in strategic and operational management areas. Bhamra et al. [23] provide a review of the topic from a multidisciplinary point of view, but with the aim of identifying opportunities and directions for application in the SME context. Meerow and Newell [24] provide a bibliographic review of studies on resilience and discuss how its findings can be applied to industrial ecology so as to design resilient industrial ecosystems. Cerè et al. [25] offer an extensive review of the studies on resilience in relation to geoenvironmental disruptive events but from a built-environment engineering perspective. Hosseini et al. [26] offer a multidisciplinary review of resilience of different complex systems with a focus on resilience measures. The complex systems analyzed in these reviews are ecological systems, social systems, engineering systems, and networks. However, except for Meerow and Newell [24], no one of these reviews explicitly focuses on resilience of complex systems, while in our review, we explicitly include only studies on complex systems.

Furthermore, there are numerous literature reviews on resilience that focus just on a single domain. For example, Righi et al. [27] offer a systematic review of engineering resilience. Kamalahmadi and Parast [28] carry out a review of supply chain resilience definitions and concepts with the aim of providing an updated framework of resilience principles and strategies. Fletcher and Sarkar [29] review studies on psychological resilience.

In the next sections, we first describe the methodology, adopt to carry out the literature review, and then discuss the results of the analysis for each research domain in details. Finally, we provide the cross-area comparison and analyze the network of citations. We end by discussing gaps in the literature and directions for future research.

2. Methodology

The study is based on a bibliographic research conducted in September 2017. The data were retrieved from Web of Science, an academic citation indexing and search service of Thomson Reuters' Web of Knowledge. In order to identify resilience related publications, we applied the keywords "Resilience" AND "Complex system∗." The query yielded 458 publications spanning from 1997 to 2017. Only journal articles published in English were considered for further analysis [24, 30], that is, 322 papers (70.3% of the results). Furthermore, we limited our analysis to the following research areas of the database, which were identified as coherent with the research domains studying resilience: (1) environmental science and ecology, (2) engineering, (3) operation research and management science, (4) computer science, (5) business and administration, and (6) psychology.

A first postprocessing of the literature data was necessary to exclude papers which were insufficiently relevant (e.g., papers where resilience was not the main research topic but was only mentioned as a suggestion for future works or the word *resilience* was among keywords, but the paper did not really address the topic) and to reduce the number of duplicated entities that occurred in the analysis. All the papers were analyzed by all the authors, and only the papers marked as relevant by all of them were included in the analysis. We applied a strict method of categorizing a publication belonging to our sample in order to accurately reflect the penetration of resilience thinking in academic research. As a consequence, 154 papers were selected as constituting the final database. A second postprocessing was necessary to eliminate the number of authors with a duplicate entry in the analysis, inserted as a result of erroneous transcription of their names. Without such a cleanup process, it would be possible for an author to be recorded as being less popular than he/she really is [31].

Each research area was first analyzed separately. For each of them, we addressed the following issues: (1) how many papers have been published and in which years, (2) what are the core journals, (3) who are the key authors and what is their collaboration network, (4) which countries are involved in the research and what is their collaboration network, and (5) what is the core literature. To perform this analysis, we used some bibliometric techniques coupled with qualitative analysis of the literature. Citation analysis [32] was used to discover and highlight the core journals, literature, and countries involved for each research area. Coauthorship analysis [33] was used to discover and highlight the key research groups and the relationships among them, as well as the relationships among countries involved in the research. The qualitative analysis was performed to identify (1) the complex systems investigated, (2) the disturbances affecting the systems, (3) the dimensions of resilience, and (4) the attributes of the system affecting resilience. Finally, we provide a qualitative description of most recent papers to identify fresh findings in each research domain.

Then, we built the citation network including all the analyzed papers, where the nodes represent the papers and a directed link from node i to node j exists when paper i cites paper j. By using centrality measures from network analysis [34], we highlighted the most important and influent articles in driving the research on resilience of complex systems. Furthermore, we traced the citation links between different research areas, in order to discover how research on the topic evolved and the level of cross-fertilization among the areas.

3. Results

The 154 papers analyzed are shown in Table 2, where bibliographical details as well as the research areas are shown for each of them. These papers were published in 89 journals and authored by 441 researchers from 37 countries over the world (Figure 1).

Table 2: Papers considered in the analysis.

Title	Reference	Source title	Publication year	Total citations	Average citations per year	Environmental science and ecology	Engineering	Operation research and management	Computer science	Business and economics	Psychology
"Predictive resilience analysis of complex systems using dynamic Bayesian networks"	[35]	*IEEE Transactions on Reliability*	2017	0	0		—		—		
"Challenges to multiteam system leadership: an analysis of leadership during the management of railway disruptions"	[36]	*Cognition Technology & Work*	2017	0	0		—				
"Did we learn about risk control since Seveso? Yes, we surely did, but is it enough? An historical brief and problem analysis"	[37]	*Journal of Loss Prevention in the Process Industries*	2017	1	1		—				
"Defining the functional resonance analysis space: combining abstraction hierarchy and FRAM"	[38]	*Reliability Engineering & System Safety*	2017	0	0		—	—			
"Team resilience as a second-order emergent state: a theoretical model and research directions"	[39]	*Frontiers in Psychology*	2017	0	0						—
"Disaster resilience as a complex problem: why linearity is not applicable for long-term recovery"	[40]	*Technological Forecasting and Social Change*	2017	0	0					—	
"Multi-level port resilience planning in the UK: how can information sharing be made easier?"	[41]	*Technological Forecasting and Social Change*	2017	0	0					—	
"Introducing flexibility to complex, resilient socio-ecological systems: a comparative analysis of economics, flexible manufacturing systems, evolutionary biology, and supply chain management"	[42]	*Sustainability*	2017	0	0		—				
"A consensus-based AHP for improved assessment of resilience engineering in maintenance organizations"	[43]	*Journal of Loss Prevention in the Process Industries*	2017	0	0		—				
"AC power flow importance measures considering multi-element failures"	[44]	*Reliability Engineering & System Safety*	2017	0	0		—	—			

Table 2: Continued.

Title	Reference	Source title	Publication year	Total citations	Average citations per year	Environmental science and ecology	Engineering	Operation research and management	Computer science	Business and economics	Psychology
"Temperate rocky subtidal reef community reveals human impacts across the entire food web"	[45]	*Marine Ecology Progress Series*	2017	1	1	—					
"Resilience in complex systems: an agent-based approach"	[46]	*Systems Engineering*	2017	0	0		—	—			
"Analyzing network topological characteristics of eco-industrial parks from the perspective of resilience: a case study"	[47]	*Ecological indicators*	2017	1	1	—					
"Transitivity demolition and the fall of social networks"	[48]	*IEEE Access*	2017	0	0		—		—		
"From math to metaphors and back again social-ecological resilience from a multi-agent-environment perspective"	[49]	*GAIA - Ecological Perspectives for Science and Society*	2017	1	1	—					
"Improving participatory resilience assessment by cross-fertilizing the resilience alliance and transition movement approaches"	[50]	*Ecology and Society*	2017	0	0	—					
"Hazard tolerance of spatially distributed complex networks"	[51]	*Reliability Engineering & System Safety*	2017	0	0		—	—			
"A Monte Carlo evolution of the Functional Resonance Analysis Method (FRAM) to assess performance variability in complex systems"	[52]	*Safety Science*	2017	3	3		—	—			
"Socio-ecological adaptation of agricultural heritage systems in modern China: three cases in Qingtian County, Zhejiang Province"	[53]	*Sustainability*	2016	0	0	—					
"Developing an integrated framework to assess agri-food systems and its application in the Ecuadorian Andes"	[54]	*Regional Environmental Change*	2016	1	0.5	—					
"Adaptive management for ecosystem services"	[55]	*Journal of Environmental Management*	2016	2	1	—					

Table 2: Continued.

Title	Reference	Source title	Publication year	Total citations	Average citations per year	Environmental science and ecology	Engineering	Operation research and management	Computer science	Business and economics	Psychology
“Comparison of static and dynamic resilience for a multipurpose reservoir operation”	[56]	*Water Resources Research*	2016	1	0.5	—					
“Remotely sensed resilience of tropical forests”	[57]	*Nature Climate Change*	2016	7	3.5	—					
“Evolutionary resilience and complex lagoon systems”	[58]	*Integrated Environmental Assessment and Management*	2016	1	0.5	—					
“Resilience allocation for early stage design of complex engineered systems”	[59]	*Journal of Mechanical Design*	2016	0	0		—				
“Breaking resilient patterns of inequality in Santiago de Chile: challenges to navigate towards a more sustainable city”	[60]	*Sustainability*	2016	2	1	—					
“A maintenance-focused approach to complex system design”	[61]	*AI EDAM-Artificial Intelligence for Engineering Design Analysis and Manufacturing*	2016	0	0		—		—		
“Challenges in the vulnerability and risk analysis of critical infrastructures”	[62]	*Reliability Engineering & System Safety*	2016	16	8		—	—			
“Computational analysis and visualization of global supply network risks”	[63]	*IEEE Transactions on Industrial Informatics*	2016	0	0		—		—		
“Designing an emergency continuity plan for a megacity government: a conceptual framework for coping with natural catastrophes”	[64]	*International Journal of Critical Infrastructure Protection*	2016	0	0		—		—		
“A framework for the future of urban underground engineering”	[65]	*Tunnelling and Underground Space Technology*	2016	0	0		—				

Table 2: Continued.

Title	Reference	Source title	Publication year	Total citations	Average citations per year	Environmental science and ecology	Engineering	Operation research and management	Computer science	Business and economics	Psychology
"Multidimensional approach to complex system resilience analysis"	[66]	*Reliability Engineering & System Safety*	2016	6	3		—	—			
"Engineered resilience for complex systems as a predictor for cost overruns"	[67]	*Systems Engineering*	2016	1	0.5		—	—			
"A graph-theoretic framework for assessing the resilience of sectorised water distribution networks"	[68]	*Water Resources Management*	2016	4	2		—				
"People-technology-ecosystem integration: a framework to ensure regional interoperability for safety, sustainability, and resilience of interdependent energy, water, and seafood sources in the (Persian) gulf"	[69]	*Human factors*	2016	2	1		—				—
"SIBBORK: a new spatially-explicit gap model for boreal forest"	[70]	*Ecological modelling*	2016	4	2	—					
"Policy support for rural economic development based on Holling's ecological concept of panarchy"	[71]	*International Journal of Sustainable Development and World Ecology*	2016	2	1	—					
"The power problematic: exploring the uncertain terrains of political ecology and the resilience framework"	[72]	*Ecology and Society*	2016	6	3	—					
"Community currency (CCs) in Spain: an empirical study of their social effects"	[73]	*Ecological Economics*	2016	0	0	—				—	
"A risk assessment approach to improve the resilience of a seaport system using Bayesian networks"	[74]	*Ocean Engineering*	2016	1	0.5		—				
"Quantifying the relationship of resilience and eco-efficiency in complex adaptive energy systems“	[75]	*Ecological Economics*	2015	1	0.33	—				—	
"Urban vulnerability and resilience in post-communist Romania	[76]	*Carpathian Journal of Earth*	2015	5	1.67	—					

Table 2: Continued.

Title	Reference	Source title	Publication year	Total citations	Average citations per year	Environmental science and ecology	Engineering	Operation research and management	Computer science	Business and economics	Psychology
(comparative case studies of iasi and Bacau cities and metropolitan areas)”		*and Environmental Sciences*									
“Resilience projects as experiments: implementing climate change resilience in Asian cities”	[77]	*Climate and Development*	2015	3	1	—					
“A unique algorithm for the assessment and improvement of job satisfaction by resilience engineering: hazardous labs”	[78]	*International Journal of Industrial Ergonomics*	2015	2	0.67		—				
“Resilience and precarious success	[79]	*Reliability Engineering & System Safety*	2015	5	1.67		—	—			
Safety culture and subcontractor network governance in a complex safety critical project”	[80]	*Reliability Engineering & System Safety*	2015	3	1		—	—			
“Hydrocomplexity: addressing water security and emergent environmental risks”	[81]	*Water Resources Research*	2015	10	3.33	—					
“Assessing temporal scales and patterns in time series: comparing methods based on redundancy analysis”	[82]	*Ecological Complexity*	2015	1	0.33	—					
“Resilience and tipping points of an exploited fish population over six decades”	[83]	*Global Change Biology*	2015	4	1.33	—					
“Network structure, complexity, and adaptation in water resource systems”	[84]	*Civil Engineering and Environmental Systems*	2015	2	0.67		—				
“The resilience of interdependent industrial symbiosis networks a case of Yixing economic and technological development zone”	[85]	*Journal of Industrial Ecology*	2015	5	1.67	—					
“Life cycle assessment and the resilience of product systems”	[86]	*Journal of Industrial Ecology*	2015	6	2	—					

Table 2: Continued.

Title	Reference	Source title	Publication year	Total citations	Average citations per year	Environmental science and ecology	Engineering	Operation research and management	Computer science	Business and economics	Psychology
"Understanding protected area resilience: a multi-scale, social-ecological approach"	[87]	*Ecological Applications*	2015	22	7.33	—					
"Resiliency analysis for complex engineered system design"	[88]	*AI EDAM-Artificial Intelligence for Engineering Design Analysis and Manufacturing*	2015	5	1.67		—		—		
"Managing hunting under uncertainty: from one-off ecological indicators to resilience approaches in assessing the sustainability of bushmeat hunting"	[89]	*Ecology and Society*	2015	1	0.33	—					
"Using fuzzy cognitive mapping as a participatory approach to analyze change, preferred states, and perceived resilience of social-ecological systems"	[90]	*Ecology and Society*	2015	16	5.33	—					
"Communication and sustainability science teams as complex systems"	[91]	*Ecology and Society*	2015	5	1.67	—					
"Regime shifts under forcing of non-stationary attractors: conceptual model and case studies in hydrologic systems"	[92]	*Journal of Contaminant Hydrology*	2014	2	0.5	—					
"Modeling and optimizing efficiency gap between managers and operators in integrated resilient systems: the case of a petrochemical plant"	[93]	*Process Safety and Environmental Protection*	2014	10	2.5		—				
"Physical infrastructure interdependency and regional resilience index after the 2011 Tohoku Earthquake in Japan"	[94]	*Earthquake Engineering & Structural Dynamics*	2014	17	4.25		—				
"Panarchy: theory and application"	[95]	*Ecosystems*	2014	45	11.25	—					
"Managing incidents in a complex system: a railway case study"	[96]	*Cognition Technology & Work*	2014	4	1		—				

Table 2: Continued.

Title	Reference	Source title	Publication year	Total citations	Average citations per year	Environmental science and ecology	Engineering	Operation research and management	Computer science	Business and economics	Psychology
"Sustainability science: accounting for nonlinear dynamics in policy and social-ecological systems"	[97]	*Clean Technologies and Environmental Policy*	2014	7	1.75	—	—				
"Managing for resilience: early detection of regime shifts in complex systems"	[98]	*Clean Technologies and Environmental Policy*	2014	12	3	—	—				
"Applying resilience thinking to natural resource management through a planning-by-doing framework"	[99]	*Society & Natural Resources*	2014	11	2.75	—					
"Linking complexity and sustainability theories: implications for modeling sustainability transitions"	[100]	*Sustainability*	2014	4	1	—					
"Comparison of ilities for protection against uncertainty in system design"	[101]	*Journal of Engineering Design*	2013	8	1.6		—				
"Consensus recovery from intentional attacks in directed nonlinear multi-agent systems"	[102]	*International Journal of Nonlinear Sciences and Numerical Simulation*	2013	7	1.4		—				
"Early warning signals: the charted and uncharted territories"	[103]	*Theoretical Ecology*	2013	40	8	—					
"Understanding resilient urban futures: a systemic modelling approach"	[104]	*Sustainability*	2013	6	1.2	—					
"Highlighting order and disorder in social-ecological landscapes to foster adaptive capacity and sustainability"	[105]	*Landscape Ecology*	2013	18	3.6	—					
"Measuring the relative resilience of subarctic lakes to global change: redundancies of functions within and across temporal scales"	[106]	*Journal of Applied Ecology*	2013	19	3.8	—					

TABLE 2: Continued.

Title	Reference	Source title	Publication year	Total citations	Average citations per year	Environmental science and ecology	Engineering	Operation research and management	Computer science	Business and economics	Psychology
"Towards affordably adaptable and effective systems"	[107]	*Systems Engineering*	2013	11	2.2		—	—			
"Transition landscapes and social networks: examining on-ground community resilience and its implications for policy settings in multiscalar systems"	[108]	*Ecology and Society*	2013	21	4.2	—					
"Temporal scales and patterns of invertebrate biodiversity dynamics in boreal lakes recovering from acidification"	[109]	*Ecological Applications*	2012	25	4.17	—					
"Microclimate and vegetation function as indicators of forest thermodynamic efficiency"	[110]	*Journal of Applied Ecology*	2012	21	3.5	—					
"A framework for identifying and analyzing sources of resilience and brittleness: a case study of two air taxi carriers"	[111]	*International Journal of Industrial Ergonomics*	2012	10	1.67		—				
"Species, functional groups, and thresholds in ecological resilience"	[112]	*Conservation Biology*	2012	20	3.33	—					
"Understanding ecohydrological connectivity in savannas: a system dynamics modelling approach"	[113]	*Ecohydrology*	2012	15	2.5	—					
"Resilience engineering of industrial processes: principles and contributing factors"	[14]	*Journal of Loss Prevention in the Process Industries*	2012	45	7.5		—				
"Assessing resilience engineering based on safety culture and managerial factors"	[114]	*Process Safety Progress*	2012	7	1.17		—				
"Agents, individuals, and networks: modeling methods to inform natural resource management in regional landscapes"	[115]	*Ecology and Society*	2012	14	2.33	—					
"Insight on invasions and resilience derived from spatiotemporal discontinuities of biomass at local and regional scales"	[116]	*Ecology and Society*	2012	15	2.5	—					

Table 2: Continued.

Title	Reference	Source title	Publication year	Total citations	Average citations per year	Environmental science and ecology	Engineering	Operation research and management	Computer science	Business and economics	Psychology
"Managing rangeland as a complex system: how government interventions decouple social systems from ecological systems"	[117]	*Ecology and Society*	2012	15	2.5	—					
"Managing for resilience"	[118]	*Wildlife Biology*	2011	35	5	—					
"Towards adaptive integrated water resources management in southern Africa: the role of self-organisation and multi-scale feedbacks for learning and responsiveness in the Letaba and Crocodile catchments"	[119]	*Water Resources Management*	2011	26	3.71		—				
"Assessing the use of functional diversity as a measure of ecological resilience in arid rangelands"	[120]	*Ecosystems*	2011	23	3.29	—					
"The use of Functional Resonance Analysis Method (FRAM) in a mid-air collision to understand some characteristics of the air traffic management system resilience"	[121]	*Reliability Engineering & System Safety*	2011	21	3		—	—			
"Disequilibrium, development and resilience through adult life"	[122]	*Systems Research and Behavioral Science*	2011	1	0.14					—	
"Improving resilience of critical human systems in CBRN emergencies: challenges for first responders"	[123]	*Systems Research and Behavioral Science*	2011	3	0.43					—	
"Can we manage for resilience? The integration of resilience thinking into natural resource management in the United States"	[124]	*Environmental Management*	2011	28	4	—					
"Reindeer management during the colonization of Sami lands: a long-term perspective of vulnerability and adaptation strategies"	[125]	*Global Environmental Change-Human and Policy Dimensions*	2011	14	2	—					

Table 2: Continued.

Title	Reference	Source title	Publication year	Total citations	Average citations per year	Environmental science and ecology	Engineering	Operation research and management	Computer science	Business and economics	Psychology
"Transition principles: experiences from the Victorian State of the Environment reporting process and relevance to sustainability in complex systems"	[126]	*Australasian Journal of Environmental Management*	2011	3	0.43	—					
"Distributed redundancy and robustness in complex systems"	[127]	*Journal of Computer And System Sciences*	2011	18	2.57				—		
"Exploiting trust-based social networks for distributed protection of sensitive data"	[128]	*IEEE Transactions on Information Forensics And Security*	2011	5	0.71		—		—		
"Promoting health and well-being by managing for social-ecological resilience: the potential of integrating ecohealth and water resources management approaches"	[129]	*Ecology and Society*	2011	29	4.14	—					
"The resilience of big river basins"	[130]	*Water International*	2011	3	0.43		—				
"Modelling the complex dynamics of vegetation, livestock and rainfall in asemiarid rangeland in South Africa"	[131]	*African Journal of Range & Forage Science*	2010	3	0.38	—					
"Design of highly synchronizable and robust networks"	[132]	*Automatica*	2010	4	0.5		—				
"Nonlinear dynamics in biopsychosocial resilience"		*Nonlinear Dynamics Psychology and Life Sciences*	2010	31	3.88						—
"Dynamic properties of complex adaptive ecosystems: implications for the sustainability of service provision"	[133]	*Biodiversity and Conservation*	2010	32	4	—					
"Identifying resilience mechanisms to recurrent ecosystem perturbations"	[134]	*Oecologia*	2010	21	2.62	—					
"Interacting regime shifts in ecosystems: implication for early warnings"	[135]	*Ecological monographs*	2010	51	6.38	—					

Table 2: Continued.

Title	Reference	Source title	Publication year	Total citations	Average citations per year	Environmental science and ecology	Engineering	Operation research and management	Computer science	Business and economics	Psychology
"Challenges of operation research practice in agricultural value chains"	[136]	*Journal of the Operational Research Society*	2010	25	3.12			—		—	
"Resilience and regions: building understanding of the metaphor"	[137]	*Cambridge Journal of Regions Economy and Society*	2010	108	13.5					—	
"Development of the multiregional inoperability input-output model (MRIIM) for spatial explicitness in preparedness of interdependent regions"	[138]	*Systems Engineering*	2010	28	3.5		—	—			
"Organizational attributes of highly reliable complex systems"	[139]	*Quality and Reliability Engineering International*	2010	3	0.38		—	—			
"Novelty, adaptive capacity, and resilience"	[140]	*Ecology and Society*	2010	26	3.25	—					
"Complex land systems: the need for long time perspectives to assess their future"	[141]	*Ecology and Society*	2010	65	8.12	—					
"Ecological and human community resilience in response to natural disasters"	[142]	*Ecology and Society*	2010	50	6.25	—					
"The politics of social-ecological resilience and sustainable socio-technical transitions"	[143]	*Ecology and Society*	2010	122	15.25	—					
"A framework for investigation into extended enterprise resilience"	[144]	*Enterprise Information Systems*	2010	34	4.25				—		
"Thresholds and multiple community states in marine fouling communities: integrating natural history with management strategies"	[145]	*Marine Ecology Progress Series*	2010	13	1.62	—					
"Resilience and thresholds in savannas: nitrogen and fire as drivers and responders of vegetation transition"	[146]	*Ecosystems*	2009	22	2.44	—					

Table 2: Continued.

Title	Reference	Source title	Publication year	Total citations	Average citations per year	Environmental science and ecology	Engineering	Operation research and management	Computer science	Business and economics	Psychology
"Integrated policies for environmental resilience and sustainability"	[147]	*Proceedings of the Institution of Civil Engineers-Engineering Sustainability*	2009	2	0.22		—				
"Collective work and resilience of complex systems"	[148]	*Journal of Loss Prevention in the Process Industries*	2009	21	2.33		—				
"Panarchy: discontinuities reveal similarities in the dynamic system structure of ecological and social systems"	[149]	*Ecology and Society*	2009	30	3.33	—					
"Towards a conceptual framework for resilience engineering"	[5]	*IEEE Systems Journal*	2009	67	7.44		—	—	—		
"The structure, function, and evolution of a regional industrial ecosystem"	[150]	*Journal of Industrial Ecology*	2009	57	6.33	—					
"Managing crisis response communication in construction projects - from a complexity perspective"	[151]	*Disaster Prevention and Management*	2009	7	0.78	—				—	
"Understanding safety and production risks in rail engineering planning and protection"	[152]	*Ergonomics*	2009	32	3.56		—				—
"Alternative stable states in Australia's wet tropics: a theoretical framework for the field data and a field-case for the theory"	[153]	*Landscape Ecology*	2009	69	7.67	—					
"Essential ecological insights for marine ecosystem-based management and marine spatial planning"	[154]	*Marine Policy*	2008	200	20	—					
"A test of the cross-scale resilience model: functional richness in Mediterranean-climate ecosystems"	[155]	*Ecological Complexity*	2008	17	1.7	—					

Table 2: Continued.

Title	Reference	Source title	Publication year	Total citations	Average citations per year	Environmental science and ecology	Engineering	Operation research and management	Computer science	Business and economics	Psychology
"Fostering resilience to extreme events within infrastructure systems: characterizing decision contexts for mitigation and adaptation"	[156]	*Global Environmental Change-Human and Policy Dimensions*	2008	105	10.5	—					
"Articulating the differences between safety and resilience: the decision-making process of professional sea-fishing skippers"	[157]	*Human Factors*	2008	28	2.8		—				—
"Adaptive harvesting in a multiple-species coral-reef food web"	[158]	*Ecology and Society*	2008	6	0.6	—					
"Not all roads lead to resilience: a complex systems approach to the comparative analysis of tortoises in arid ecosystems"	[159]	*Ecology and Society*	2008	6	0.6	—					
"Governing fisheries as complex adaptive systems"	[160]	*Marine Policy*	2008	84	8.4	—					
"Marine protected areas: a governance system analysis"	[161]	*Human Ecology*	2007	76	6.91	—					
"Creating a transparent, distributed, and resilient computing environment: the OpenRTE project"	[162]	*Journal of Supercomputing*	2007	1	0.09		—		—		
"Vulnerability analysis in environmental management: widening and deepening its approach"	[163]	*Environmental Conservation*	2007	6	0.55	—					
"Cross-scale interactions and changing pattern-process relationships: consequences for system dynamics"	[164]	*Ecosystems*	2007	88	8	—					
"Focusing the meaning(s) of resilience: resilience as a descriptive concept and a boundary object"	[165]	*Ecology and Society*	2007	235	21.36	—					
"Resilience, panarchy, and world-systems analysis"	[166]	*Ecology and Society*	2007	31	2.82	—					
"Evaluating discontinuities in complex systems: toward quantitative measures of resilience"	[167]	*Ecology and Society*	2007	20	1.82	—					

Table 2: Continued.

Title	Reference	Source title	Publication year	Total citations	Average citations per year	Environmental science and ecology	Engineering	Operation research and management	Computer science	Business and economics	Psychology
"Understanding and managing complexity risk"	[168]	*MIT Sloan Management Review*	2007	16	1.45					—	
"Understanding and managing the complexity of urban systems under climate change"	[169]	*Climate Policy*	2007	31	2.82	—					
"Australian pastoralists in time and space: the evolution of a complex adaptive system"	[170]	*Ecology and Society*	2006	23	1.92	—					
"Biodiversity and land use change on the Causse Mejan, France"	[171]	*Biodiversity and Conservation*	2006	8	0.67	—					
"Collapse and reorganization in social-ecological systems: questions, some ideas, and policy implications"	[172]	*Ecology and Society*	2006	86	7.17	—					
"A handful of heuristics and some propositions for understanding resilience in social-ecological systems"	[173]	*Ecology and Society*	2006	352	29.33	—					
"Theoretical steps towards modelling resilience in complex systems"	[174]	*Computational Science and Its Applications - ICCSA 2006, PT 1*	2006	6	0.5				—		
"Indicating retrospective resilience of multi-scale patterns of real habitats in a landscape"	[175]	*Ecological Indicators*	2006	20	1.67	—					
"Stable periodic orbits associated with bursting oscillations in population dynamics"	[176]	*Positive Systems, Proceedings*	2006	8	0.67				—		
"A systems model approach to determining resilience surrogates for case studies"	[177]	*Ecosystems*	2005	72	5.54	—					
"The use of discontinuities and functional groups to assess relative resilience in complex systems"	[178]	*Ecosystems*	2005	76	5.85	—					
"Change and identity in complex systems"	[179]	*Ecology and Society*	2005	58	4.46	—					

Table 2: Continued.

Title	Reference	Source title	Publication year	Total citations	Average citations per year	Environmental science and ecology	Engineering	Operation research and management	Computer science	Business and economics	Psychology
"Sustainability indicators as a communicative tool: building bridges in Pennsylvania"	[180]	*Environmental Monitoring and Assessment*	2004	13	0.93	—					
"Landscape change in the southern Piedmont: challenges, solutions, and uncertainty across scales"	[181]	*Conservation Ecology*	2003	17	1.13	—					
"Grazing management, resilience, and the dynamics of a fire-driven rangeland system"	[182]	*Ecosystems*	2002	146	9.12	—					
"First-order reliability method for estimating reliability, vulnerability, and resilience"	[183]	*Water Resources Research*	2001	42	2.47	—					
"Prediction in complex communities: analysis of empirically derived Markov models"	[184]	*Ecology*	2001	59	3.47	—					
"A fuzzy logic model to predict coral reef development under nutrient and sediment stress"	[185]	*Conservation Biology*	1998	36	1.8	—					

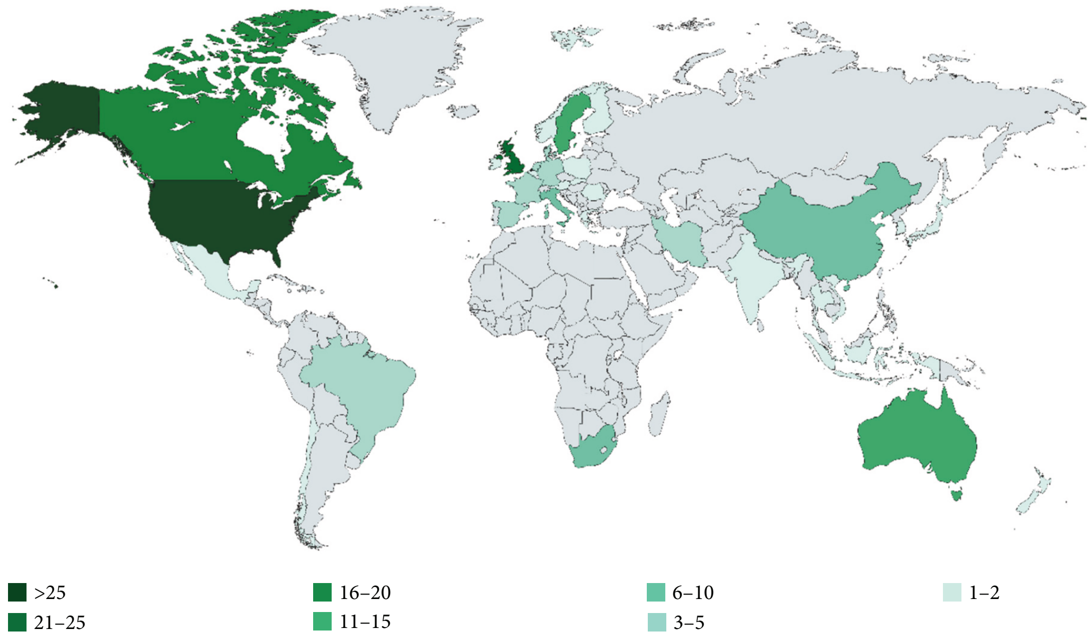


Figure 1: Distribution of publications by country.

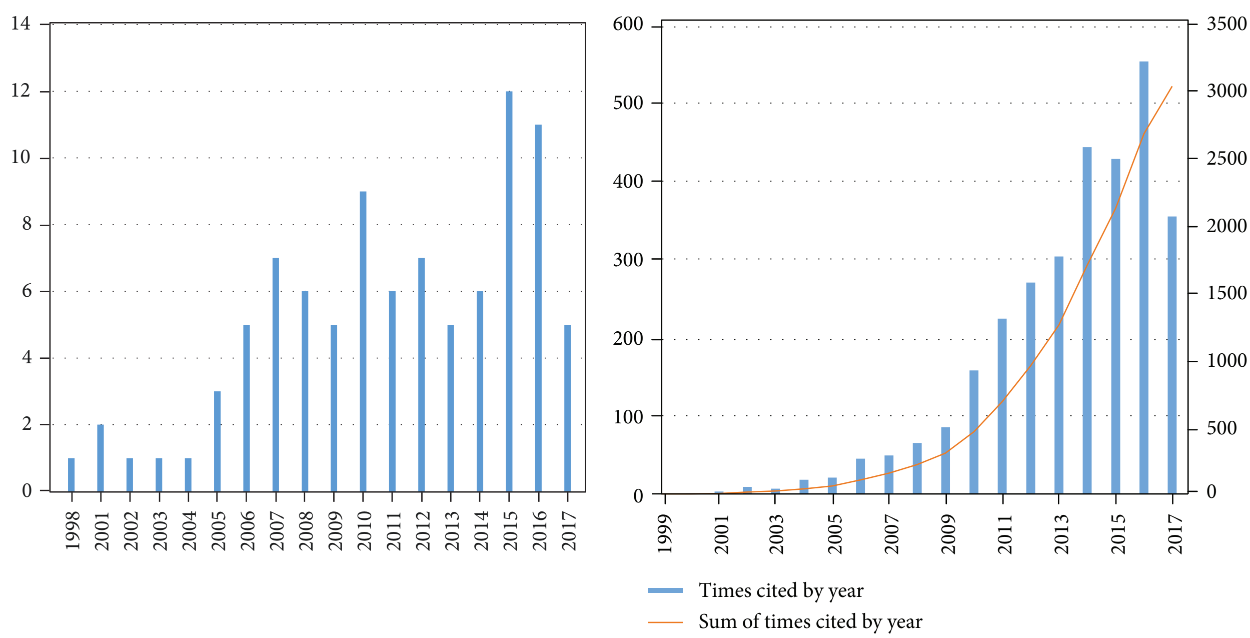


Figure 2: (a) Number of papers published by year; (b) times cited by year and sum of time cited by year.

3.1. Analysis for Each Research Area

3.1.1. Environmental Science and Ecology. 93 papers were published between 1998 and 2017 in 44 journals (Figure 2(a)). Within the top five journals, *Ecology and Society* (IF 2.8, *H*-index 110) published 24 papers (25.81% of the published papers), *Ecosystems* (IF 4.198, *H*-index 121) published 7 papers (7.53%), *Sustainability* (IF 1.789, *H*-index 35) published 5 papers (5.38%), *Water Resources Research* (IF 4.397, *H*-index 158) published 3 papers (3.23%), and *Journal of Industrial Ecology* (IF 4.123, *H*-index 74) published 3 papers (3.23%). 12 other journals published 2 papers each, while 27 journals published 1 paper each. The number of papers published per year increases over time with a peak in 2015 (12 papers).

Papers in this area gained in total 3025 citations, and on average, each paper was cited 32.53 times. Figure 2(b) shows the number of citations gained per year as well as the sum of times cited by year. An exponential positive trend is shown for both these measures. In particular, since 2011, more than

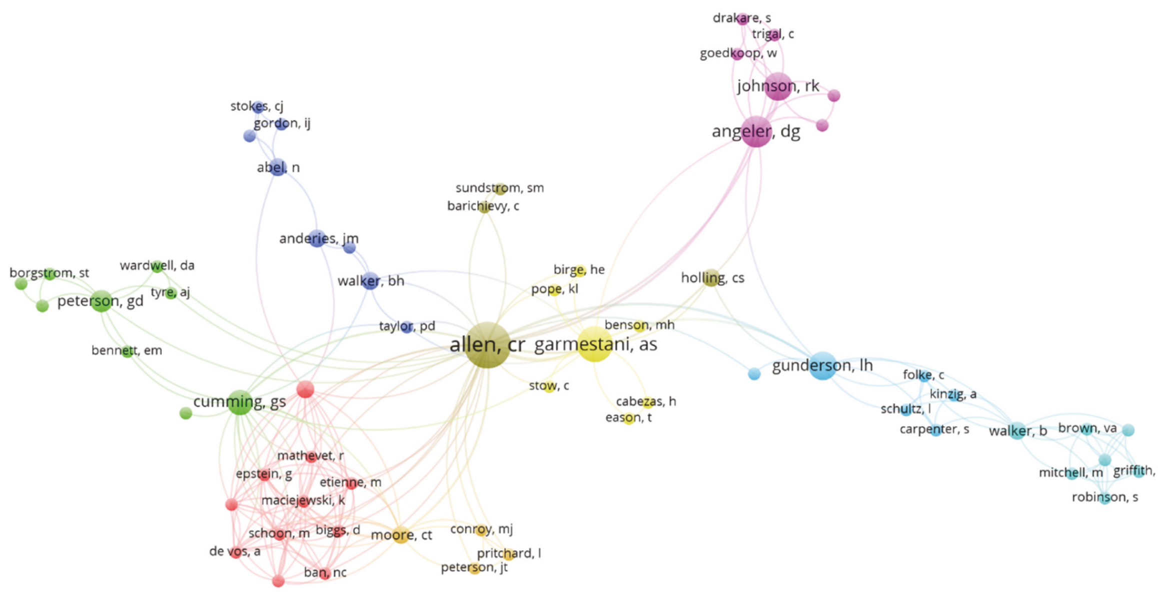


Figure 3: Coauthorship map for papers belonging to the research area "environmental science and ecology."

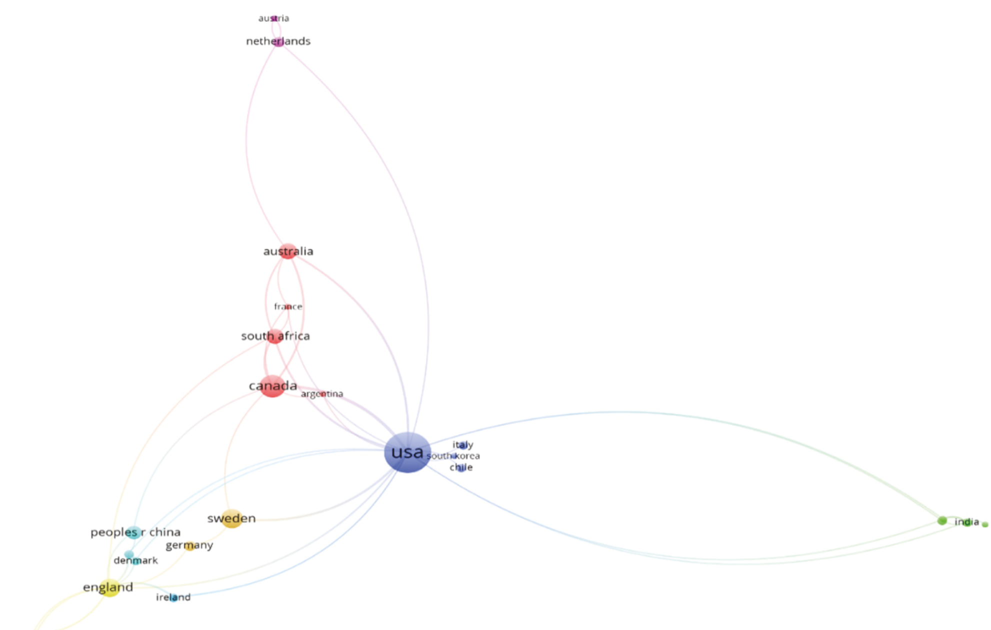


Figure 4: Relationships among countries concerning papers belonging to the research area "environmental science and ecology."

100 citations per year have been gained by these papers. This year is topical identifying the time in which the concept starts to grow fast and thus to be relevant in the literature.

270 researchers were found among the authors of the analyzed papers. Figure 3 shows the coauthorship map, where each node corresponds to one researcher and two nodes are linked if the corresponding researchers coauthored at least one paper. In particular, the size of the node is proportional to the number of authored papers. The figure highlights 8 main research groups spread over the world; it also shows that the most relevant researchers in the scientific community are Craig R. Allen (University of Nebraska, USA), Ahjond S. Garmestani (EPA National Risk Management Research Laboratory, USA), David G. Angeler (Sveriges Lantbruksuniversitet, Sweden), Lance H. Gunderson (Emory University, USA), and Graeme S. Cumming (University of Cape Town, South Africa). In fact, in addition to having a scientific productivity higher than the average (size of the node), these authors cooperated in a larger number of research groups (number of links).

Figure 4 shows the countries involved in the research and the collaborative relationships among them. In particular, each node in the figure corresponds to a country, and the size of the node is proportional to the number of papers authored by at least one researcher of that country. 34 countries over the world are involved in the research: USA (44 papers), Canada (12), Sweden (10), England (9), Australia (8), South Africa (6), China (5), Scotland (3), Netherlands (3), Germany (3), Spain (2), New Zealand (2), Japan (2), Italy (2), Ireland (2), Indonesia (2), India (2), Denmark (2), Chile (2), Vietnam (1), Thailand (1), South Korea (1), Slovakia (1), Singapore (1), Romania (1), Poland (1), Norway (1), Greece (1), France (1), Finland (1), Brazil (1), Belgium (1), Austria (1), and Argentina (1). The figure clearly highlights the relevant role played by the USA in this research area, for both the number of papers published by researchers belonging to USA organizations and the cooperation with many foreign researchers.

As the core literature, the five papers with the highest number of citations are briefly presented. Walker et al. [173] (349 citations, 29.08 citations per year) developed 14 propositions about resilience in social-ecological systems, which represent the authors' understanding of how these complex systems change and what determines their ability to absorb disturbances in either their ecological or their social domains. For each proposition, a list of research questions for future research is proposed. Brand and Jax [165] (235 citations, 21.36 citations per year) reviewed the variety of definitions proposed for the concept of resilience within environmental sustainability science and suggested a classification according to the specific degree of normativity. They found 10 definitions of resilience, distinguishing between purely ecological definitions (4 definitions) and those which are also used in the context of other fields such as economy and sociology (6 definitions). They also distinguished 3 categories of definitions, reflecting whether the definition is in accordance with either a genuinely descriptive concept, a genuinely normative concept, or a hybrid concept, in which descriptive and normative connotations are intermingled. Crowder and Norse [154] (200 citations, 20 citations per year) addressed the resilience of marine ecosystems. They recognized that marine populations and ecosystems exhibit complex system behaviors, and they proposed an ecosystem-based approach for maintaining and recovering biodiversity and integrity. Their approach focused on the heterogeneity of biological communities and their key components, the interaction among these components, and the key processes that maintain them, as well as on the heterogeneity of human uses. Anderies et al. [182] (145 citations, 9.06 citations per year) developed a stylized mathematical model that captures the essential features of a fire-driven rangeland system, which is simple enough for resilience to be clearly defined. With the model, they explored how ecological, economic, and management factors influence the resilience of the system. Smith and Stirling [143] (122 citations, 15.25 citations per year) addressed the role of technology for the resilience of socioecological and sociotechnical systems. The paper has three purposes: (1) elaborating the roles played by technology in social-ecological resilience; (2) discussing the importance of carefully determining the differences between the socioecological and sociotechnical systems, in terms of problem framings and intellectual histories, as well as the similarities; and (3) identifying in transition management some critical governance challenges that are valid for social-ecological research.

The complex systems analyzed within this research area are natural ecosystems (e.g., riverine, forests, lakes, sea, and coral reefs) and socioecological systems (e.g., agricultural systems and industrial ecosystems). These systems are mainly perturbed by the following types of disturbances: human behaviors (e.g., fishery activities), climate change (e.g., an increase in water temperature), and changes in the economic and social environment. Resilience of these systems is mainly associated with the following dimensions: resistance, recovery, and adaptive capacity. Resistance refers to the ability of individual species or communities to resist or survive with given factors in the face of disturbance. Recovery is the process by means of which an ecosystem bounces back to its predisturbance status. Adaptive capacity is the internal ability of the system to reorganize its internal features so that returning to the predisturbance state is not required. In such a case, disturbance can be also considered an opportunity; it transfers the system into a new, more desirable state.

Different attributes of ecosystems influencing resilience have been investigated to date. These can be classified referring to individual, population, community, ecosystem, and process levels [186]. Individual attributes refer to characteristics of its species including growth rate, size, and biological ability of adaptation to disturbance. At population and community levels, three main attributes are mostly considered: diversity, redundancy, and connectivity. These are more commonly considered to confer to ecosystems, a resilience to climate change, even though the complex nature of an ecosystem can make the system's behavior unpredictable. In particular, genetic diversity is associated with resistance to change and recovery, while functional and response diversity, offering alternatives and opportunities to the system in face of disturbance, support adaptive capacity. Redundancy fosters the ability of ecosystems to maintain the provision of a function when facing failure. For example, if a species is removed, redundancy assures that the ecological function provided by that species may persist within the system, because of the compensation offered by the other species providing the same function. Redundancy thus confers resistance and stability to ecosystems. Connectivity refers to interactions between species at community and population scales and also includes the connectivity of habitat types and ecosystems. In the face of climate change, connectivity is generally found to enhance recovery and adaptive capacity. For example, Mumby and Hastings [187] show that connectivity with mangroves can increase the ability of coral reef ecosystems to recover from disturbance caused by hurricanes. However, it is also recognized that a too high level of connectivity may lead to rigidity with negative consequences on adaptability. Connectivity can also become a double-edged sword, because it could allow pathogens and other invasive organisms to spread, which could radically change the structure and dynamics of ecological assemblages [188].

Focusing on the most recent studies published in this area, two papers (50% of the total) apply network theory to model ecosystems and use network measures to characterize it (e.g., chain length, link density, and degree centrality). In Pérez-Matus et al. [45], a network of feeding relationships is constructed for 147 species that inhabit subtidal reefs of

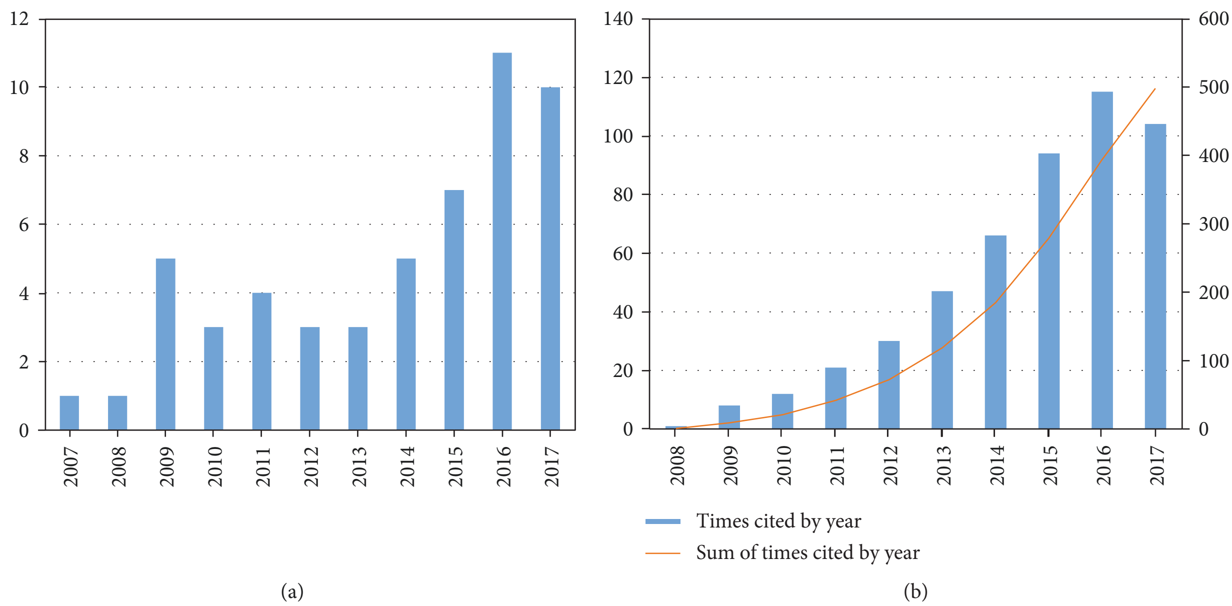


FIGURE 5: (a) Number of papers published by year; (b) times cited by year and sum of times cited by year.

the coast of central Chile. Network theory is shown to offer a comprehensive representation of the trophic links that connect species within local communities. It is also useful to investigate the effect of fishery pressure on the stability of a food web. In the study by Li and Xiao [47], network theory is employed to model the Ningdong Coal Chemical Eco-industrial Park and to analyze the structural properties of this industrial symbiosis network from the perspective of resilience. It extends the previous studies working on resilience in the eco-industrial networks under disruptive scenarios [189–191]. A new index measuring the importance of a particular node in the network is proposed, which integrates node-level metrics (node degree, in-degree, out-degree, betweenness, and integrated node centrality) with the ecological factor of the node, that is, the node impact on eco-efficiency.

The other two studies [49, 50] propose new conceptual frameworks with the aim of applying resilience for sustainable development. In particular, the study by Sellberg et al. [50] compares and integrates two methods for assessing resilience of complex systems having complementary strengths: the transition movement and the resilience alliance's resilience assessment. Since the resilience assessment's conceptual framework generates context-specific understanding of resilience but provides little guidance on how to manage the transformation process, using it in combination with transition movement's methods is suggested, as the latter offer practical tools promoting learning and participation. This approach is shown to be useful for practitioners seeking to apply resilience for sustainable development.

3.1.2. Engineering. 53 papers were published between 2007 and 2017 (Figure 5(a)) in 32 different journals. Within the top four journals, *Reliability Engineering System Safety* (IF 3.153, H-index 105) published 8 papers (15.09% of the papers published), *Systems Engineering* (IF 0.5, H-index 36) and *Journal of Loss Prevention in the Process Industries* (IF 1.818, H-index 56) published 4 papers (7.55%) each, and *Journal of Industrial Ecology* (IF 4.123, H-index 74) published 3 papers (5.66%). Six journals published 2 papers each, while 22 journals published 1 paper each. The number of papers increases rapidly, reaching a peak in 2016 (11 papers).

Papers in this area gained in total 498 citations, and on average, each paper was cited 9.4 times. Figure 5(b) shows the number of citations gained per year as well as the sum of times cited by year. A positive trend in the number of published papers since 2013 is shown. The number of citations grows with an exponential trend.

138 researchers were found among the authors of the analyzed papers. Figure 6 shows the coauthorship map. From this figure, several issues can be noticed: (1) the research is highly fragmented, because of the high number of research groups without any interaction among them, and (2) the absence of a leading researcher as a point of reference. In fact, 128 researchers published only one paper each, 9 published 2 papers each, and only Ali H. Azadeh (University of Tehran, Iran) published 3 papers.

Figure 7 shows the countries contributing involved in the research and the relationships among them. 20 countries over the world are involved in the research: USA (26 papers), England (8), China (4), Italy (4), Iran (4), Brazil (3), South Africa (2), Netherlands (2), France (2), Canada (2), Australia (2), Vietnam (1), Sweden (1), Spain (1), Singapore (1), Scotland (1), Saudi Arabia (1), Mexico (1), Finland (1), and Denmark (1). From the Figure 7, it can be noticed the central role played by USA, which cooperates with almost all the other countries. Scant collaborative relationships among the other countries can be noticed.

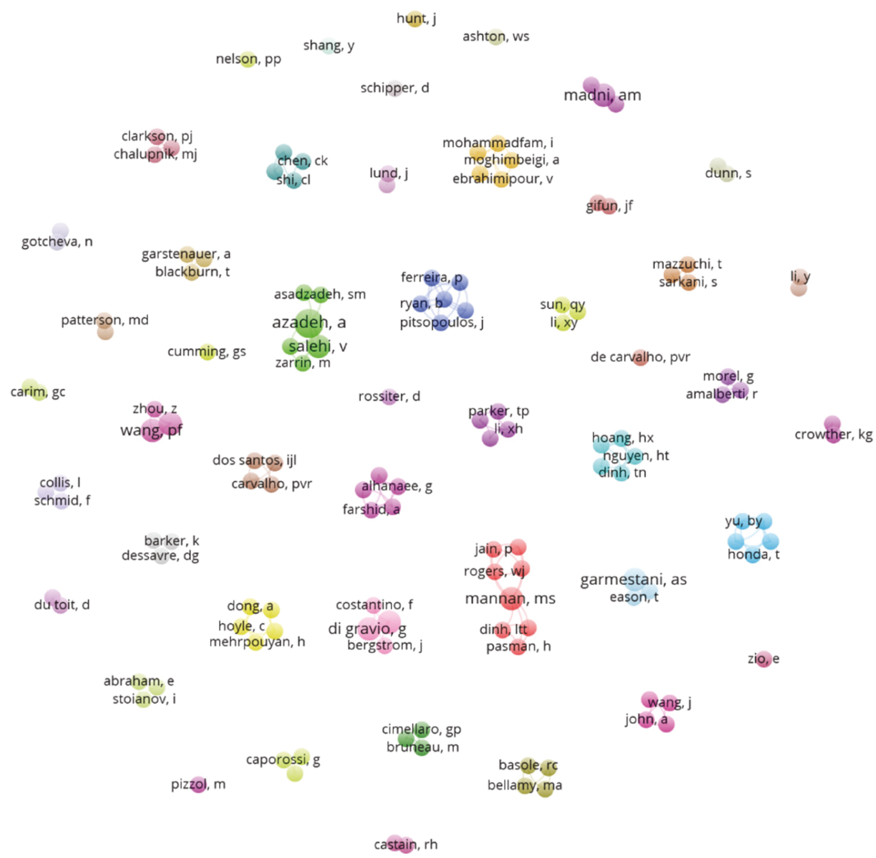


Figure 6: Coauthorship map for papers belonging to the research area "engineering."

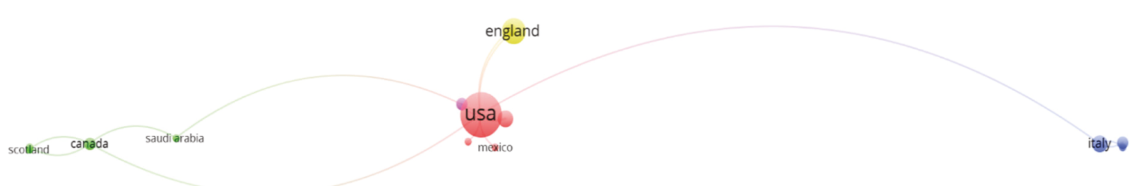


Figure 7: Relationships among countries concerning papers belonging to the research area "engineering."

As the core literature, the five papers with the highest number of citations are briefly presented. Madni and Jackson [5] (67 citations, 7.44 citations per year) developed a conceptual framework for analyzing and understanding the resilience of engineering systems. The framework identifies system attributes affecting the system resilience, disruptions, methods adopted to address resilience, and metrics to measure resilience. Dinh et al. [14] (45 citations, 7.5 citations per year) proposed six principles (flexibility, controllability, early detection, minimization of failure, limitation of effects, and administrative controls/procedures) and five factors (design, detection potential, emergency response plan, human factor, and safety management) that contribute to the resilience of a design or process operation. Both principles and factors were identified based on literature reviews and expert opinions. Wilson et al. [152] (32 citations, 3.56 citations per year) addressed how rail engineering systems can be affected by disruptions generated by human factor issues (e.g., work environment, communications, procedures and responsibilities, organization, and training). Morel et al. [157] (28 citations, 2.8 citations per year) investigated how the resilience of fishery systems depends on the decision-making processes of humans that are part of these systems. Crowther and Haimes [138] (28 citations, 3.5 citations per year) provided a holistic, methodological framework based on the multiregional inoperability input-output model, with which to model the interdependencies among economic sectors within a given region and among different regions. Each region is in fact recognized as a complex, interconnected, and interdependent economic system of systems that includes multiple stakeholders, spans multiple subregions, and produces a very large number of commodities and services. This model is useful when studying the cascade effects of perturbation across different economic sectors and regions because it highlights significant cross-sectorial and cross-regional interdependencies.

The complex systems analyzed within this research area can be subdivided into two categories: (1) physical infrastructures, such as electric power networks, telecommunication networks, water and gas distribution networks, transport infrastructures, rail networks, air traffic control systems, and petrochemical plants, and (2) production systems and supply chains. Both these kinds of complex system are vulnerable to a broad range of events, which can be classified as intentional or unexpected: terroristic attacks, sabotages, technical failures, human failures, accidents, natural events, changes in technology, society, and environment.

The resilience dimensions associated with these complex systems are mainly stability, robustness, vulnerability, safety, and adaptability. Stability refers to the ability of the system to preserve or return to the same equilibrium state when a failure occurs. Robustness is the property of the system to maintain its basic functionality when subjected to failures and voluntary attacks. Vulnerability concerns the sensitivity of the system to threats and stress. It measures the degree of loss and damage due to the impact of hazards. Safety is a condition of an engineering system associated with lack (or limited levels) of injury to people and of property damage, achieved through a defense process of hazard identification and risk management. Adaptive capacity involves transformation, learning, self-organization, and positive feedback at multiple scales.

Redundancy and connectivity are considered as the main drivers of the resilience of engineering systems, because they are found to positively impact on adaptability and robustness. Connectivity, that is, the ability of different elements to be linked by different pathways, protects the network from disconnection in the event of a failure making an element of the system unavailable. For example, Porse and Lund [84] suggest promoting physical connectivity of the California water system to build a resilient system that could adapt quickly to changing conditions. However, it should be borne in mind that high connectivity can become critical in the event of large cascading failures. These occur when the unavailability of an element generates overloads and malfunctioning of those elements that are connected to it [192]. Redundancy, that is, a number of elements providing the same function to the system, allows the system to switch from the damaged element to a working one, thus maintaining system function.

The relationship between system topology and resilience in terms of robustness and vulnerability, in case of node removal, has mainly been investigated by employing network theory. Network theory gives tools to detect important nodes and links using different metrics such as centrality measures, the shortest path between node pairs, and pair-wise connectivity. It is also useful for quantifying the effect of firm removal on overall network performance.

Looking at the most recent papers published in this field, one aspect is noteworthy; 63% of them also belong to another research field, with the great majority of them (71%) being classified in the field of operation research and management science. This is explained by the typology of tools adopted to model and analyze resilience, which come from this discipline. We briefly comment these papers in the next sections. Here, we focus on the studies belonging only to the engineering field. They are quite different but have in common in the fact that some organizational and social factors characterizing the system are introduced into the analysis on resilience.

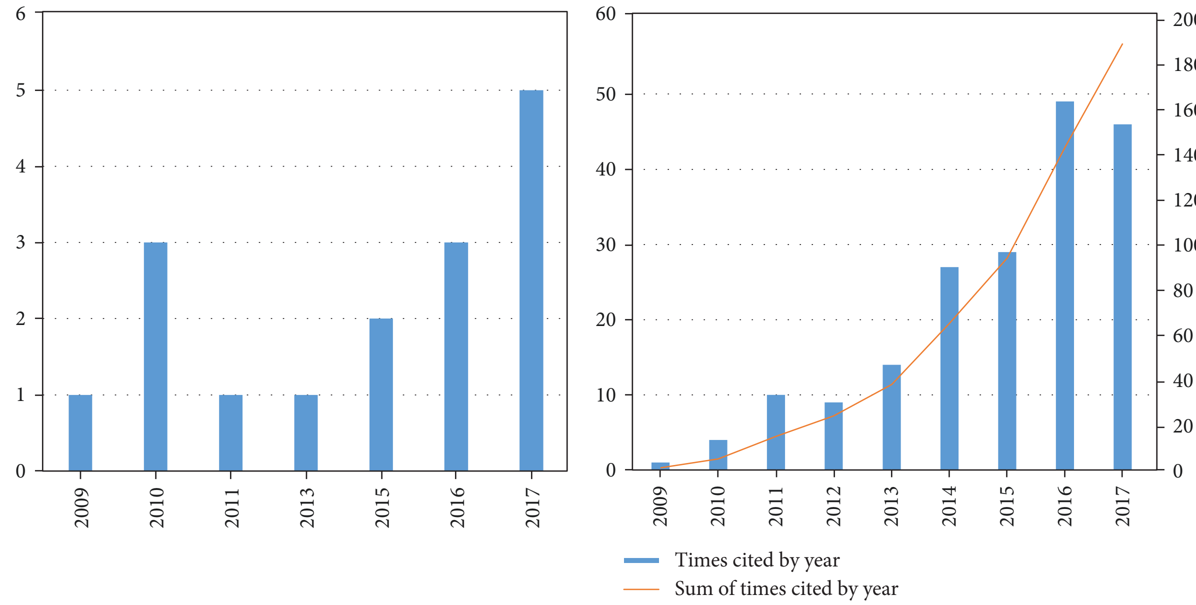
Schipper [36] investigates the influence of leadership on the efficacy of polycentric adaptive control. In particular, the study explores the behaviors and functions of leader teams during the management of two large-scale disruptions in the Dutch railway system. It shows that polycentric control cannot instantly be organized, simply by introducing a leader team above the component teams. To be effective, leadership requires teamwork between component and leader teams in which the component teams should facilitate the leader teams in their role.

Jain et al. [37] present a resilience-based analysis of the Seveso incident and develop a process resilience analysis framework, which is aimed at advancing risk assessment and management techniques through integration of technical and social factors. These factors involve coordination among the government, the management, the operation team, and the public along with the process plant and its components. The study suggests that the integration of technical and social factors helps understand critical situations better and thus supports resilience of sociotechnical process systems. Asokan et al. [42] propose a dynamic conceptual framework emphasizing the role of flexibility in creating resilience in the field of sustainability science. It is argued that flexibility affects robustness and transformation. It can allow for a correct balance between the two extremes. Flexibility emphasizes rerouting flows or functions, overlapping functions and multifunctionality, and many options or alternatives for decision-making.

3.1.3. Operation Research and Management Science. 16 papers were published between 2009 and 2017 (Figure 8(a)) in 6 journals: *Reliability Engineering System Safety* (IF 3.153, H-index 105) published 8 papers (50%), *Systems Engineering* (IF 0.5, H-index 36) published 4 papers (25%), while *Safety Science* (IF 2.246, H-index 75), *Quality and Reliability Engineering International* (IF 1.366, H-index 44), *Journal of the Operational Research Society* (IF 1.077, H-index 83), and *IEEE Systems Journal* (IF 3.882, H-index 39) published 1 paper each. Articles in this area gained in total 189 citations, and on average, each paper was cited 11.81 times. Figure 8(b) shows the number of citations gained per year as well as the sum of times cited by year. A positive increasing trend of citations is recognizable.

Figure 9 shows the coauthorship map, highlighting that research is highly fragmented (14 research groups with no interaction among them) and that a reference point for the research does not exist. 38 researchers were involved in the research: 35 of them only wrote one paper, while Giulio Di Gravio (Università degli Studi di Roma La Sapienza, Italy), Riccardo Patriarca (Università degli Studi di Roma La Sapienza, Italy), and Azad M. Madni (USC and Intelligent Systems Technology, USA) wrote 2 papers each.

The research involved 11 countries over the world: USA (9 papers), Italy (3), England (2), Sweden (1), China (1), Netherlands (1), Mexico (1), France (1), Finland (1), Brazil (1), and Australia (1). However, scant cooperation among countries was found: the USA cooperates with Mexico,



(a) (b)

Figure 8: (a) Number of papers published by year; (b) times cited by year and sum of time cited by year.

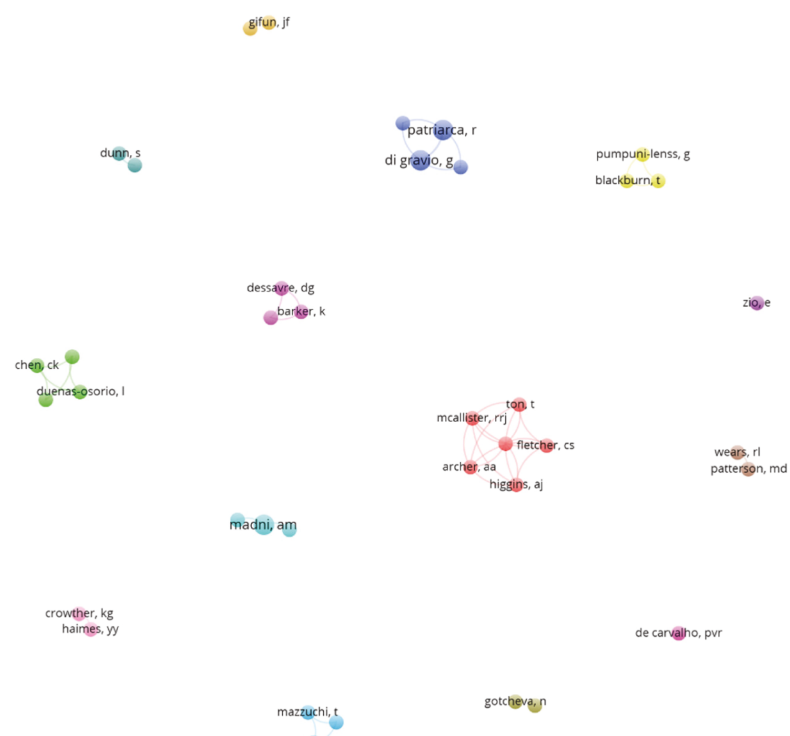


Figure 9: Coauthorship map for papers belonging to the research area "operation research and management."

China, England, and Netherlands; no other relationships were found.

The two papers with the highest number of citations are Madni and Jackson [5] and Crowther and Haimes [138], already presented above in Section 3.1.2, because they are classified in the database as belonging to multiple areas (engineering, operation research and management science, and computer science for the paper by Madni and Jackson and engineering and operation research and management science for the paper by Crowther and Haimes). Here, the other 3 papers with the highest number of citations are briefly presented. Higgins et al. [136] (25 citations, 3.12 citations per year) focused on agricultural value chains as complex adaptive systems. In particular, they undertook a critical stocktake of operation research applications in this field to date and reflected on (1) their capacity to address the complexity inherent in agriculture value chains and (2) their contribution to the evaluation of chain sustainability and resilience. De Carvalho [121] (21 citations, 3 citations per year) described how the functional resonance analysis method can be used to analyze resilience characteristics of a complex system, such as the Brazilian Air Traffic Management System, and to provide useful insights about system safety and resilience. The goal of the functional resonance analysis method is to understand how systems function in order to design more resilient systems, that is, systems that can cope with dangerous variability causing the drift of the system to states of higher risk or to design management systems to detect the drift and assist in formulating appropriate responses before an accident occurs. Zio [62] (16 citations, 8 citations per year) provided a systematic view on the problem of vulnerability and risk analysis of critical infrastructures such as energy transmission and distribution networks, telecommunication networks, transportation systems, and water and gas distribution systems. All these infrastructures are recognized as complex systems designed to function for long periods. He also discussed the concept of resilience for such infrastructures, arguing that the complexity of these systems is a challenging characteristic, which calls for the integration of different modeling perspectives and new analytical approaches.

The complex systems analyzed within this research area concern supply networks, critical infrastructures, such as energy distribution systems and transportation systems, and management systems. The latter are sociotechnical systems characterized by the existence of multiple actors including both human operators and engineering infrastructures. Similarly to the categories above, these complex systems are affected by diverse types of disturbances ranging from natural disasters to human accidents to mechanical failures. The main dimensions of resilience include flexibility, vulnerability, recovery, and adaptive capacity. In this context, flexibility is defined as the capacity of the system (e.g., transportation system, supply chain, and production network) to take different positions to respond better to change.

Different attributes of these systems are shown to affect resilience. Diversity of the system, measured in terms of the number of components and the number of links among them, is associated with high flexibility and low vulnerability. Redundancy is also shown to enhance resilience improving flexibility and adaptive capacity [12]. For example, having multiple suppliers, increasing safety stock, design overcapacity, and adopt backup suppliers are strategies promoting redundancy and, consequently, resilience in supply chains [28].

Structural features of supply networks affecting resilience have been investigated using network theory [193, 194]. The latter is also used to conceptualize supply network disruptions and resilience [195] and compare the effect of the network structure (block-diagonal, centralized, scale-free, and diagonal) on network resilience.

Further drivers of resilience of these systems concern governance attributes. The main findings suggest that a limited degree of top-down hierarchy and level of control in decision-making processes enhance adaptive capacity and self-organization. Furthermore, it is found that a high level of information sharing among the actors is critical in order to build resilient supply chains [28].

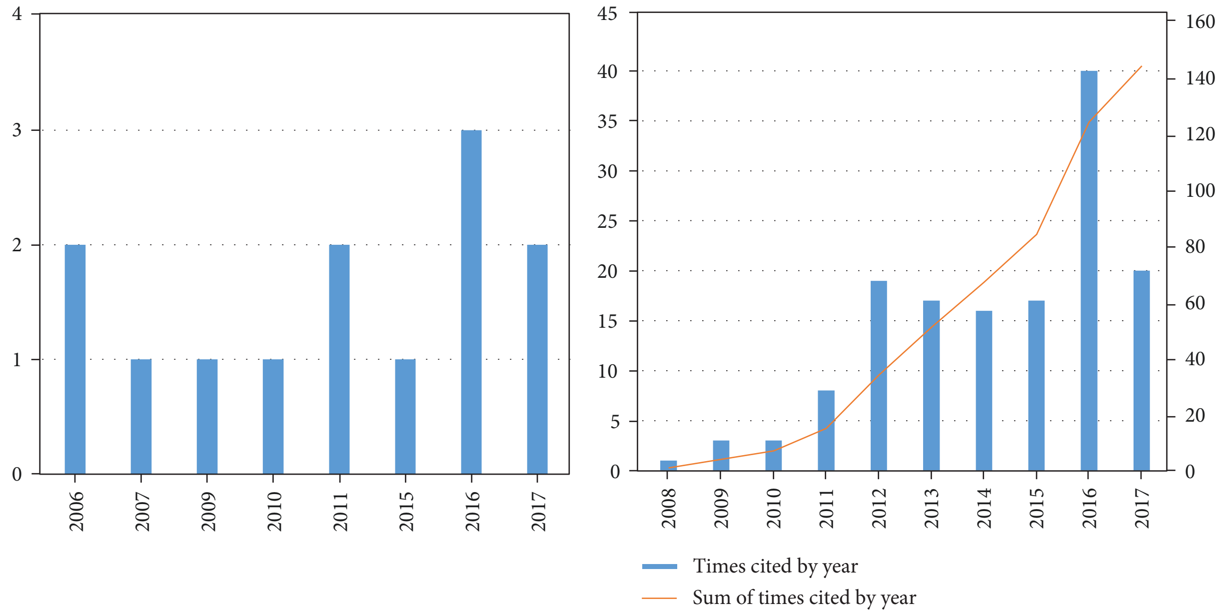
Recent papers (also belonging to the engineering field) investigate resilience of critical infrastructures such as air traffic management, energy system, and power flow systems. Two studies [38, 52] apply the functional resonance analysis method (FRAM), a framework recently developed for complex system analysis which is aimed at defining the couplings among functions of the system in a dynamic way. Both papers propose a revision of the method highlighting critical functions and critical links between functions, so contributing to safety analysis and management.

The paper by Li et al. [44] proposes an alternative current- (AC-) based power flow element importance measure by considering multielement failures. A cascading failure model is presented based on AC power flow able to capture dynamic phenomena of power systems and assess their reliability. The measure is aimed at informing decision-makers about key components, while improving cascading failure prevention, system backup settings, and overall resilience.

The other two recent papers employ network theory to study resilience in the face of natural disruptions. Pumpuni-Lenss et al. [46] combine network analysis and agent-based modeling to measure the performance of the system as it responds to disruptive events due to broken arcs. Various resilience measures are proposed to quantify system resilience based on the computation of maximum flow data, fraction of operating arcs, system impact, and arc degradation. This system model can be applied to the management of response strategies for network disruptions. Dunn and Wilkinson [51] present a new methodology for quantifying the reliability of complex systems when subjected to hazard, using techniques from network graph theory. The novelty of this study relies in introducing the spatial dimension to network analysis. A number of algorithms for generating a range of synthetic spatial networks with different topologies (scale-free and exponential) and spatial characteristics are proposed. The influence of nodal location and the spatial distribution of highly connected nodes on hazard tolerance is analyzed. The findings show that uniform with distance nodal configurations is vulnerable to hazards located over the geographical center of the network. The uniform with area nodal configurations provides the same resilience to spatial hazards located both in the geographical center and the periphery.

3.1.4. Computer Science. Thirteen papers were published between 2008 and 2017 (Figure 10(a)), each of them published in a different journal. This means that core journals for this research area do not exist. Papers in this area gained in total 144 citations; on average, each paper was cited 11.08 times. Figure 10(b) shows the number of citations gained per year as well as the sum of times cited by year. Citations increase after 2012 with a peak in 2016.

Figure 11 shows the coauthorship map, highlighting that, also in this area, the research is highly fragmented; 11



(a) (b)

FIGURE 10: (a) Number of papers published by year; (b) times cited by year and sum of time cited by year.

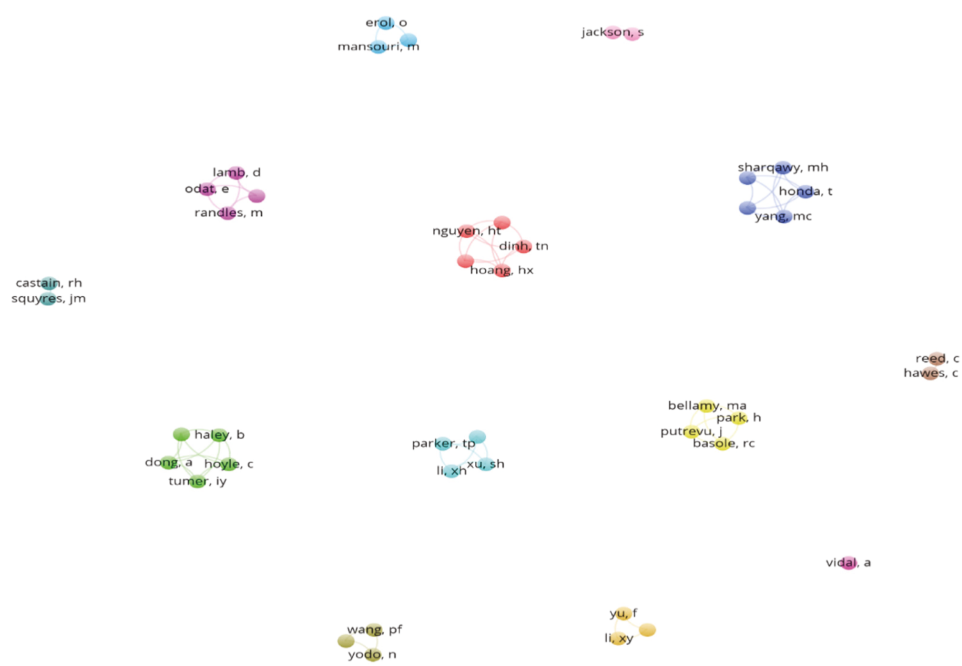


FIGURE 11: Coauthorship map for papers belonging to the research area “computer science.”

research groups were found, composed of up to 5 researchers, without any interaction among them. Each of the 43 researchers wrote one paper, meaning that a reference point for the research does not exist.

The research involved 9 countries over the world: the USA (9 papers), Saudi Arabia (2), China (2), England (1), Vietnam (1), Scotland (1), France (1), Canada (1), and Australia (1). However, Figure 12 shows that scant cooperation among countries exists.

The papers with the highest number of citations is Madni and Jackson [5], already presented in Section 3.1.2. Erol et al. [144] (34 citations, 4.25 citations per year) proposed a framework to investigate resilience in the context of extended enterprises. The proposed framework is based on the expanded application of two primary enablers of enterprise resilience: (1) the capability of an enterprise to connect systems, people, processes, and information in a way that allows enterprise to become more connected and responsive to the

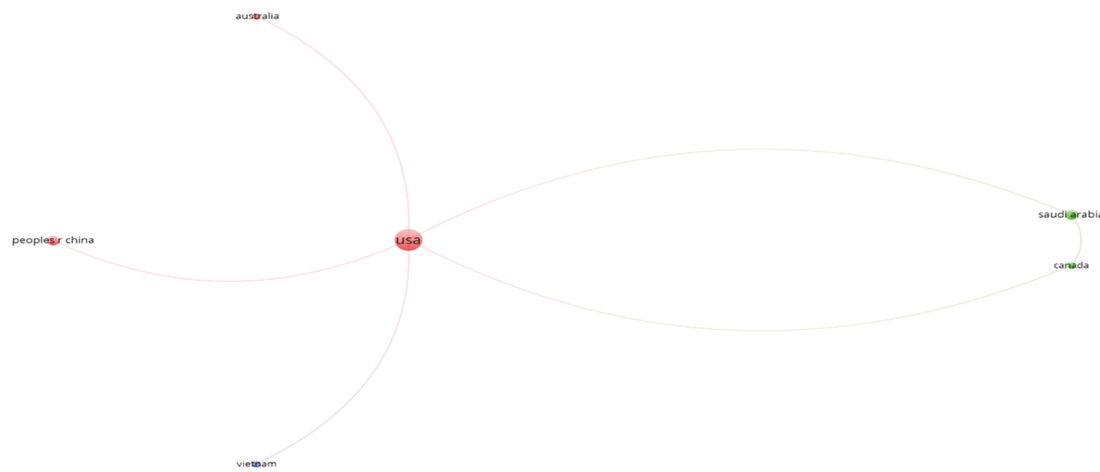


Figure 12: Relationships among countries concerning papers belonging to the research area "computer science."

dynamics of its environment, stakeholders, and competitors and (2) the alignment of information technology with business goals. Radles et al. [127] (18 citations, 2.57 citations per year) addressed the role of distributed redundancy in improving complex system resilience. While regular redundancy refers to the function of identical elements, distributed redundancy refers to different elements facilitating the same outcomes. Through simulations, they showed that distributed redundancy can be enhanced by increasing the average algebraic connectivity across the components in a network. The results are applied to a specific application where active clustering of like services is used to aid load balancing in a highly distributed network. Using the described procedure is shown to improve performance and distribute redundancy. Vidal [176] (8 citations, 0.8 citations per year) focused on repetitive crises that perturb the periodic evolution of tritrophic slow-fast systems. They analyzed the singular points and bifurcations of the fast dynamics, the various behaviors of the full system depending on its parameters, and the existence and unicity of periodic bursting orbit in those different cases. Hawes and Reed [174] (6 citations, 0.5 citations per year) demonstrated that it is possible to integrate individual-based modeling approaches of theoretical ecology, artificial intelligence techniques in multiagent systems, and channel theory in philosophical logic into a coherent theoretical framework for tackling the hard problem of resilience in complex systems.

The complex systems analyzed within this research area mainly concern computer networks, including cloud-based systems, Internet of Things devices, and information flow systems. Recently, social networks characterized by both the existence of individuals and computers as nodes of the system have attracted the interest of scholars. The resilience of these systems is studied concerning intentional or involuntary disturbances, usually targeted to single nodes such as human attacks or engineering failures.

The main dimensions of resilience investigated are recovery and adaptive capacity. The main variables influencing resilience are structural features characterizing the network. In particular, redundancy of links and node centrality are found to be critical to enhance resilience of these systems. Social trustworthiness is a further variable analyzed with respect to social networks, which is mainly critical for data security and network survival.

Looking at recent studies, Nguyen et al. [48] investigate the vulnerability of social networks using network theory. Critical nodes and edges are identified by computing the number of connected triples (or triangles) that are broken, when a failure (either random or intentional) occurs, causing changes in the network's organization and leading to the unpredictable dissolving of the network. Connected triples is a fundamental network property that has been shown to be relevant to a variety of topics, such as mutual relationships in social networks, reliable data transmission in communication networks, and flexibility of supply networks. Two algorithms are proposed, which are highly performing and scalable.

3.1.5. Business and Economics. 10 papers were published between 2007 and 2017 (Figure 13(a)) in 7 journals: 3 of them published 2 papers (*Technological Forecasting and Social Change*, IF 2.625, *H*-index 78; *Systems Research and Behavioral Science*, IF 1.034, *H*-index 34; and *Ecological Economics*, IF 2.965, *H*-index 151), the remaining 4 published 1 paper each. Papers in this area gained in total 161 citations, and on average, each paper was cited 16.1 times. Figure 8(b) shows the number of citations gained per year as well as the sum of times cited by year. This number has been constantly increasing since 2008, also with an increasing trend.

Figure 14 shows the coauthorship map, highlighting that research is highly fragmented; 11 research groups were found, composed of up to 6 researchers, without any interaction among them. Furthermore, we did not find any researcher as a reference point. In fact, each of the 27 researchers wrote only one paper.

The research involved only 7 countries over the world: USA (3 papers), Australia (2), Spain (1), Singapore (1), Finland (1), England (1), and Austria (1).

As the core literature, the 5 papers with the highest number of citations are briefly presented. Pendall et al. [137] (108 citations, 13.5 citations per year) analyzed two common frameworks underlying resilience thinking in the context of regional resilience: (1) *equilibrium analysis*,

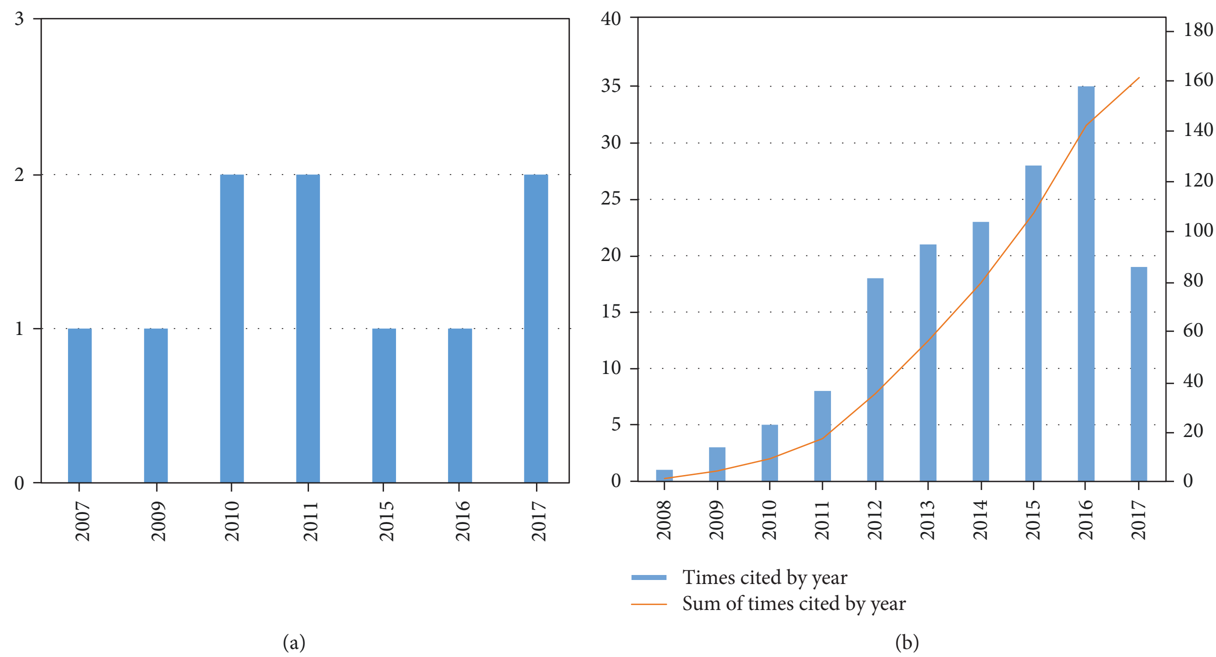


Figure 13: (a) Number of papers published by year; (b) times cited by year and sum of time cited by year.

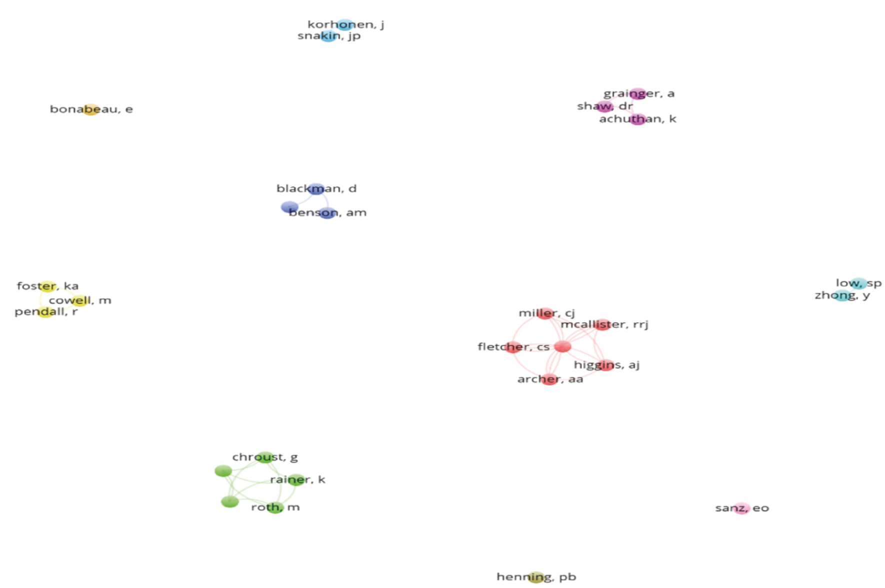


Figure 14: Coauthorship map for papers belonging to the research area "business and economics."

which emphasizes the likelihood of a phenomenon exhibiting resilience by "returning to normal," as in a single equilibrium system, or shifting to "new" or "no" normals in multiple equilibrium systems; and (2) *complex adaptive systems analysis*, which emphasizes how multiple elements interact to produce dynamic feedbacks, making a system more or less adaptable, that is, resilient to stress. They identify four fundamental themes of resilience: equilibrium, systems' perspective, path dependence, and the long view. The paper by Higgins et al. [136] has already been presented in Section 3.1.3. Bonabeau [168] (16 citations, 1.45 citations per year) focused on complex systems composed of different firms interacting among each other. He addressed how improving resilience of the system can mitigate business risks of the involved firms. In particular, he addressed system's modularity and diversity as two antecedents of resilience. Zhong and Pheng Low [151] (7 citations, 0.78 citations per year) proposed a conceptual framework for understanding the underlying pattern of communication behavior and decisions of human systems in response to a crisis and for investigating how to enhance the organization's adaptability and resilience in the event of a crisis, focusing on the role of control parameters. Chroust et al. [123] (3 citations, 0.45 citations per year) pointed out that

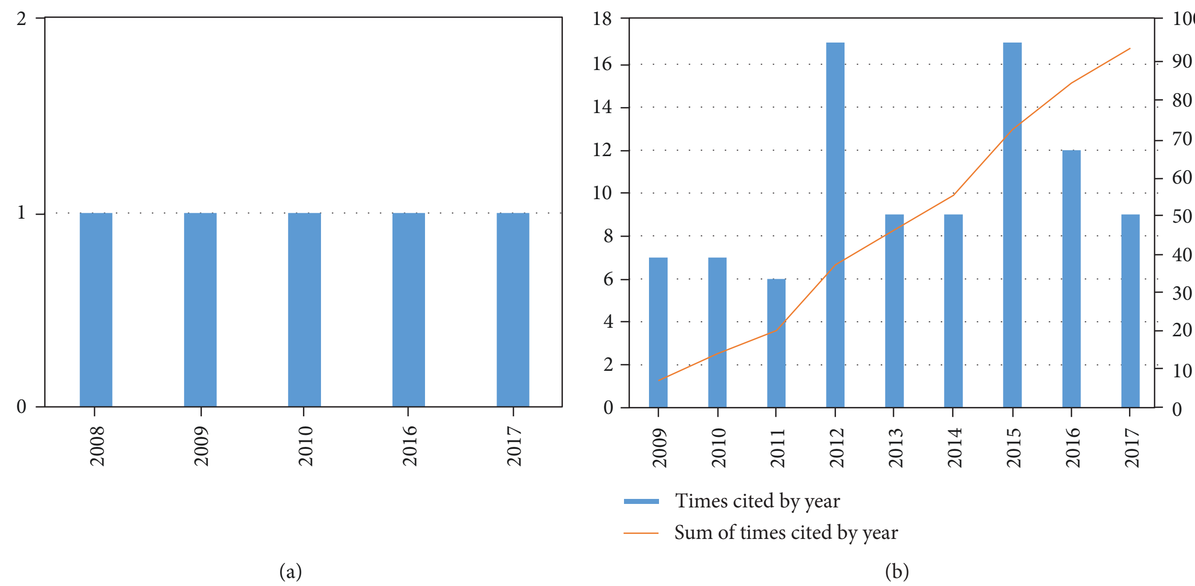


FIGURE 15: (a) Number of papers published by year; (b) times cited by year and sum of time cited by year.

a complex system can be made resilient by the addition of an intervention system that intervenes in the case of loss of dependability. In particular, they investigate the role of first responders (i.e., fire brigade, ambulance services, and police forces) as intervening systems in the case of chemical, biological, radiological, or nuclear incidents, aimed at providing resilience. They identified the main properties of the above-mentioned incidents and their implications for the activities of first responders both in training and real assignments.

The complex systems analyzed within this research area involve single firms, industries, regions, ports, value chains, and also individuals. These complex systems are often characterized by the coexistence of diverse types of actors including humans, industrial infrastructures, companies, computers, and information and communication technologies. Disturbances include natural disasters such as hurricanes and tides, human actions (e.g., acts of terrorism), and social, economic, and technological changes occurring in the environment. In these studies, resilience is mainly associated with adaptability and recovery.

Given the diversity of the systems analyzed, there is a wide variety in the drivers of resilience investigated. These include human factors characterizing the individuals belonging to the system (e.g., level of anxiety, tension, social power, and economic status) as well as physical features referring to the network topology as well as social and organizational features.

As to the topological attributes, redundancy, density, and modularity are investigated as some of the most important factors affecting self-organization and, in turn, resilience. Network theory coupled with agent-based modeling and dynamical system modeling has been suggested as an appropriate tool for gaining insights into system dynamics under different and dynamic conditions [136].

Recently, organizational and social features have been analyzed as important attributes of resilience. These include collaboration, communication, and visibility among the actors, which are found to positively affect supply chain resilience. All of them are fundamental to guarantee that timely critical information is available to decision-makers when a disturbance occurs requiring intervention. Social capital, norms, and trust facilitate coordination and enable self-organization, thus fostering adaptability.

The two most recent papers both focus on social and organizational variables. Blackman et al. [40] investigate the resilience of post disaster communities emphasizing the role played by three factors: (1) new actors, (2) new forms of social capital, and (3) coproduction. New actors emerge after disasters playing a role as catalyst by collaborating with local governments and media to disseminate the idea for recovery. They also connect people outside of their network and contribute to the development of social capital. This positively influences recovery. Coproduction is about creating a new value for community towards the recovery involving all the actors in community. A centralized approach where solutions are proposed by the government is shown to increase tensions and lead to less effective long-term recovery.

Shaw et al. [41] focus on port resilience planning and the importance of information sharing between stakeholders about key dependencies and alternative actions undertaken to achieve resilience in face of disasters. The approach proposed to information sharing uses the *subjectivity of information* from a supplier's perspective and from a user's perspective. A centralized method of information sharing that is used in a decentralized way is designed. This helps stakeholders to access the information they need, so that they work more effectively.

3.1.6. Psychology. Surprisingly, only 5 papers were published between 2008 and 2017 (Figure 15(a)) in 4 journals: *Human Factors* (IF 2.219, *H*-index 88) published 2 papers whereas *Nonlinear Dynamics, Psychology, and Life Sciences* (IF 1.289, *H*-index 22), *Frontiers in Psychology* (IF 2.323, *H*-index 58), and *Ergonomics* (IF 1.818, *H*-index 86)

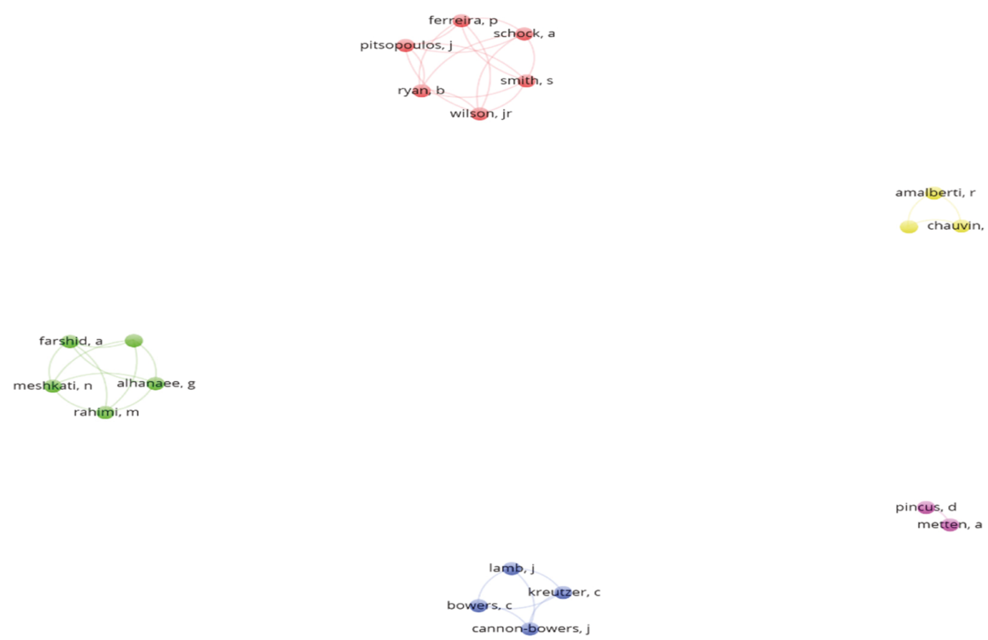


Figure 16: Coauthorship map for papers belonging to the research area "psychology."

published one paper each. Note that there were no papers published in the interval time 2011–2015, in countertrend compared with the other domains, which experienced a growth in those years.

Papers in this area gained in total 93 citations, and on average, each paper was cited 18.6 times. Figure 15(b) shows the number of citations gained per year as well as the sum of times cited by year. Except for two years (2012, 2015), the number of citations stays quite low and with no clear trend of growth.

Figure 16 shows the coauthorship map, highlighting that 5 research groups exist, without any interaction among them. Furthermore, an author reference point for the research does not exist. In fact, each of the 20 researchers wrote only one paper.

Only 4 countries are involved in the research: USA (3 papers), France (1), England (1), and Australia (1). No relationships among countries were found.

As the core literature, the 4 papers with the highest number of citations are briefly presented, because the paper by Wilson et al. [152] has already been presented in Section 3.1.2. Pincus and Metten [196] (31 citations, 3.88 citations per year) analyzed resilience in the context of nonlinear dynamical systems showing complex interactions of biological, psychological, and social factors over time, aimed at understanding how researchers can apply nonlinear dynamical system techniques and practitioners can use the resulting evidence to improve patient care. Four data analytic techniques from nonlinear dynamical systems (time-series analysis, state-space grids, catastrophe modeling, and network modeling) were used. These techniques are contrasted with respect to the information they may provide about some common processes underlying resilience. Morel et al. [157] (28 citations, 2.8 citations per year) analyzed the articulation of resilience to the notion of safety in complex systems. First, they provided the analysis of the theoretical framework linking the concepts of resilience and safety; then, they studied the relationship between resilience and safety in conditions of extreme risk using observations and simulations in the example of professional sea fishing. Meshkati et al. [69] (2 citations, 1 citation per year) developed a methodology to identify the interdependencies of human and organizational subsystems of multiple complex, safety-sensitive technological systems, and their interoperability in the context of sustainability and resilience of ecosystems.

The complex systems analyzed in this research area concern individuals and groups of individuals, such as teams. Disruptions regard stressful events happening during the normal life or incidents occurring to complex engineering systems which require humans (managers and operators) to intervene. For these complex systems, resilience is mainly associated with adaptive capacity, viewed as individual or collective ability to adapt to change.

Resilience of these systems mainly depends on behavioral and psychological traits of individuals, such as problem-solving abilities, optimism, and other features of human personalities. For managers and operators, experience and skills are considered important in this regard. Team resilience is associated with features characterizing the group of individuals such as collective efficacy, cohesion, social support, trust, and psychological safety.

Only one paper was published in 2017. It concerns team resilience [39], that is, how groups collectively and positively adapt to adversity. The authors propose a conceptual model of team resilience as a mediator of the relationship between other team emergent states (cohesion, collective efficacy, shared mental models, familiarity, culture, and adaptability) and outcomes during times of stress. Outcomes include cognitive ability, social ability, physical health, psychological health, error avoidance, and desire

Table 3: Summary of the main features for each research area.

Research areas	Papers	Interval time	Journals	Citations	Authors	Prominent country
Environmental science and ecology	93	1998–2017	44	3025	270	USA
Engineering	53	2009–2017	32	498	138	USA
Operation research and management science	16	2008–2017	8	189	38	USA
Computer science	13	2007–2017	13	144	43	USA
Business and economics	10	2008–2017	7	161	27	USA
Psychology	5	2008–2017	4	93	20	USA

to remain. Thus, resilience is the result of these other states, and it enables the team to achieve either positive or negative outcomes.

3.2. Cross-Area Comparison. In this section, we make a comparison among the different research areas. Table 3 summarizes the main results of previous analyses. It appears clear that environmental science, ecology, and engineering are the fields of study in which the topic received most attention. In these domains, both the number of papers published and the number of citations received increased over time with an exponential trend. The areas of operation research and management science, computer science, and business and economics are novel domains of interest but considerably less important. Resilience in psychology has a marginal role even though the number of citations received on average by the papers is quite high. In all research areas, the USA plays the prominent role.

3.3. Research Methodologies. Figure 17 shows the research methodologies adopted by papers for each research area. Five research methodologies were identified: (1) case study, (2) conceptual model, (3) simulation, (4) survey, and (5) analytic model. On average, the conceptual model is the most adopted methodology, followed by the case study, the simulation, survey, and analytic model. We note that conceptual model is the methodology most adopted by papers in environmental science and ecology (51.06% of the papers in this area use such an approach), computer science (46.15%), business and economics (50%), and psychology (40%, ex aequo with case study). Case study is the most adopted methodology for papers in engineering (47.06%) and operation research and management (43.75%). The use of surveys seems to be restricted to papers belonging to operation research and management area (6.25%), while the analytic approach is significantly used only in computer science (7.69%). Finally, simulation is mainly used by papers in operation research and management (18.75%) and computer science (23.08%).

Conceptual models are mainly employed when the research aim is to provide notions of resilience and to theoretically identify the drivers of resilience. Case studies are mainly used to provide clarification and confirmation of the relationship between drivers and resilience. The studies using simulation offer dynamic models reproducing complex system behavior and are employed to measure resilience. Surveys are mainly adopted to develop assessment measures both qualitative and quantitative in nature.

3.4. Citation Analysis. Figure 18 shows the citation network among the papers belonging to our population. Each node of the network depicts one paper, while links among papers denote citations among them; for instance, a directed link from node 2 to node 44 means that the paper corresponding to node 2 cites the paper corresponding to node 44.

123 links among nodes were found in the network. Table 4 shows the centrality measures computed on the network. Papers with the highest in-degree centrality, that is, the most cited papers, are Allen et al. [178] (17 citations), Stow et al. [167] (8 citations), and Garmestani et al. [149] (7 citations). These papers all belong to the "environmental science and ecology" research area and are the most influential for the study of resilience of complex systems. Papers with the highest out-degree centrality, that is, papers providing the highest number of citations, are Sun et al. [64] (12 citations), Slight et al. [71] (7 citations), Li and Li [117] (5 citations), Brännlund and Axelsson [125] (5 citations), and Brock and Carpenter [135] (5 citations). These papers use concepts developed in previous studies most extensively. Papers with the highest betweenness centrality in the network are Allen et al. [95], Angeler et al. [134], and Brand and Jax [165]. These papers belong to the "environmental science and ecology" area and are critical because they are nodes that convey information in the network.

We also analyze the network in Figure 18 to identify clusters, that is, groups made up of papers with links among each other and without any link with papers external to the group. 13 clusters were found (Table 5).

We found that papers belonging to a given research area tend to cite papers belonging to the same research area. This means that the research fields are still isolated from each other with little integration and cross-fertilization. Despite the recognized multidisciplinary nature of complex systems' resilience, very few studies seem to rely on and exploit this feature.

A few cross-citations among different areas were found, although this practice is recent. In fact, almost all papers citing papers belonging to different areas have been published since 2014. All citation relationships among different research areas are graphically highlighted in Figure 19. Two papers belonging to the "engineering" area cite papers belonging to other areas. Yodo and Wang [59] cite Patterson and Wears [79] ("engineering" and "operation research and management") and Miller et al. [113] ("environmental science and ecology") referring to applications of the concept of resilience in several fields. Cumming [130] uses Cumming

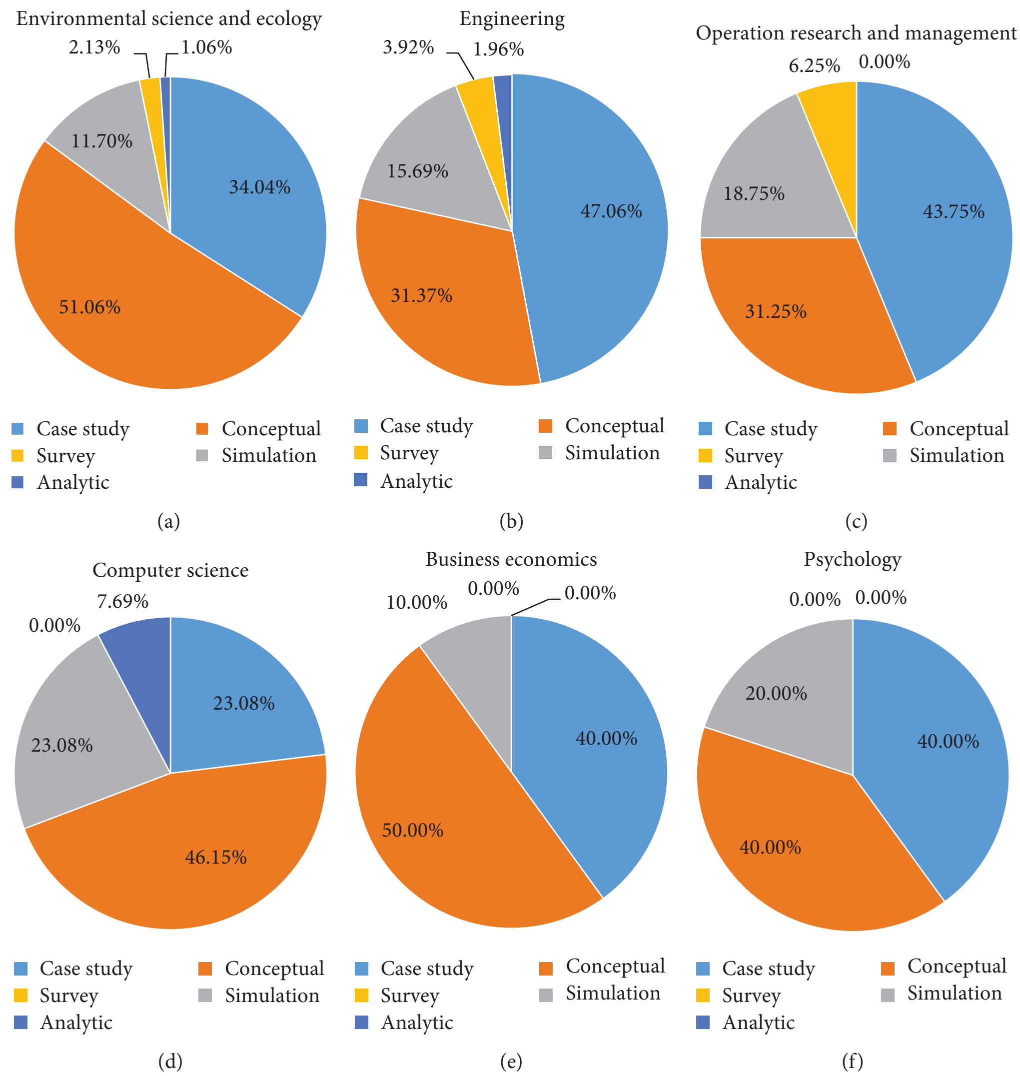


Figure 17: Research methodologies adopted for each research area: (a) environmental science and ecology; (b) engineering; (c) operation research and management; (d) computer science; (e) business and economics; (f) psychology.

and Coller's [179] ("environmental science and ecology") definition of resilience and methodological approach in order to find the most important elements for the system. Three papers belonging to "environmental science and ecology" cite papers belonging to other areas. Asokan et al. [42] and Davoudi et al. [58] cite Pendall et al. [137] ("business and economics"), highlighting the importance of human behavior and policy measures in affecting resilience of ecosystems. In their review of panarchy theory, Allen et al. [95] cite the study by Eason et al. [98] ("environmental science and ecology" and "engineering") as an improved method to detect discontinuities. Bowers et al. [39] ("psychology") cite Vidal et al. [148] ("environmental science and ecology" and "engineering") about the role of explicit communication as one of the main inputs enabling resilience in social systems. Basole et al. [63] ("computer science" and "engineering") cite Zhao et al. [104] ("environmental science and ecology") about the importance of taking into account resilience due to the criticality of healthy supply networks to firm survival and growth. Yodo et al. [35] ("computer science" and "engineering") use the definition of resilience provided by Dessavre et al. [66] ("engineering" and "operation research and management") and cite Yodo and Wang [59] ("engineering") to highlight the fact that interdependencies among components in a system play a critical role on the resilience of that system, since they allow an initial failure to be redistributed to other components in the system. Higgins et al. [136] ("operation research and management" and "business and economics") use the methodology adopted by Anderies et al. [182] ("environmental science and ecology") to quantify the thresholds where the interactions between dynamic components may flip to drive a system away from a dynamic equilibrium to which it is attracted and towards a different equilibrium. Garmestani [97] and Eason et al. [98] ("environmental science and ecology" and "engineering") refer to the concept of panarchy (originated by Gunderson and Holling [10]) citing the study by Garmestani et al. [149] ("environmental science and ecology").

It is not surprising that papers in the "environmental science and ecology" research area are cited by papers in

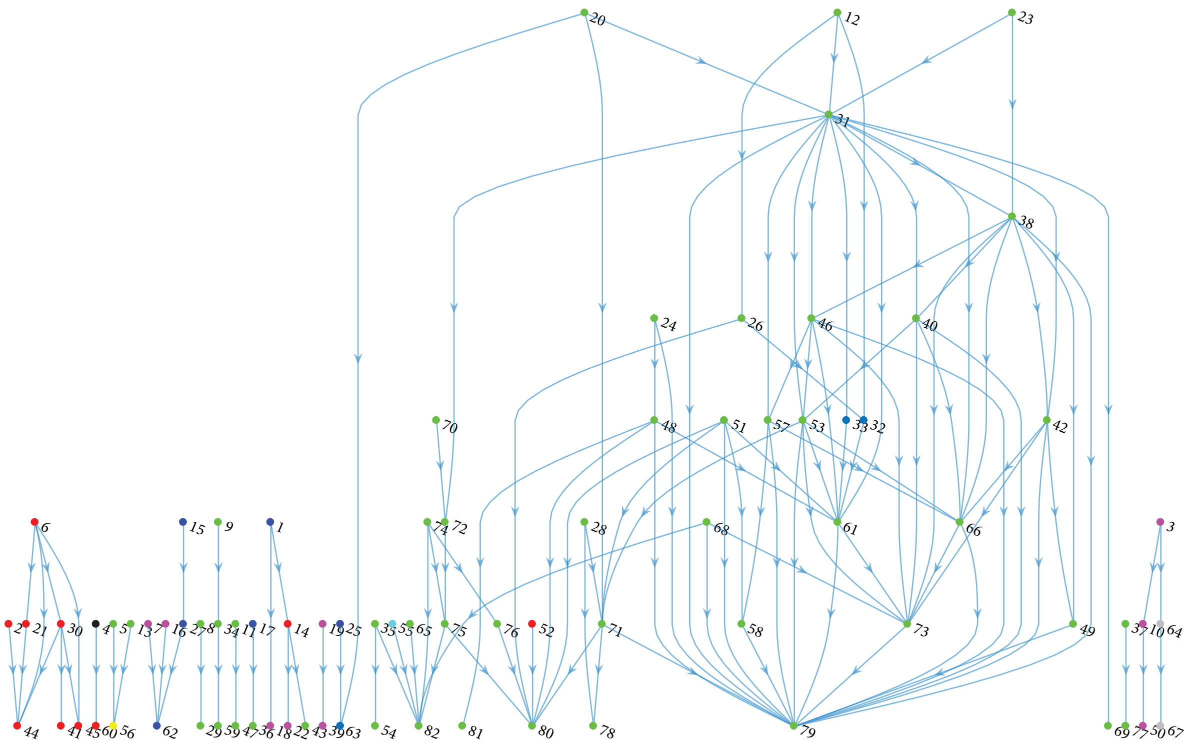


Figure 18: Citation network among the papers belonging to our population.

different areas because this area is where the concept originated. For this reason, we expected this type of cross-area citations, though we also anticipated a higher number than was actually found. Interestingly, we note that the papers in this research area, instead, cite papers in different areas. This shows that the "environmental science and ecology" research area is far from maturity and opens to new insights from other areas.

Furthermore, we combine cross-area citations with information concerning the number of citations provided in Table 2. We found that papers receiving citation by papers belonging to other areas are cited over the average number for all papers cited, ceteris paribus. This means that papers integrating different theoretical perspectives allow a better performance to be achieved, and this suggests directions for future research.

4. Conclusions, Gaps of the Literature, and Future Research Directions

This paper offered a systematic literature review of the studies concerning the resilience of complex systems by analyzing multiple research areas, with the aim of identifying intellectual communities, leading scholars, key knowledge, specific dimensions, and attributes of resilience. Our analysis provided an updated state of the art of the literature, characterized by a multidisciplinary nature and without emphasis on a specific field of study, as is commonly the case in the literature.

The analysis revealed that a common understanding of resilience across research fields is still lacking, even though some dimensions of resilience (recovery and adaptive capacity) as well as some attributes of the systems (redundancy and connectivity) influencing resilience are shared by a number of research areas.

Our analysis has allowed us to identify important gaps in the literature to be filled. Except for "environmental science and ecology," in all the other fields, we found that research is highly fragmented and carried out by a number of isolated research groups. This represents a strong limitation for the development of new studies in all these research areas. We also discovered a further gap in the literature, not previously identified, by analyzing the network of citations of the papers. We expected a higher number of citations between papers belonging to different research areas and especially from other areas towards the "environmental science and ecology" field. Surprisingly, we found a very limited number of cross-area citations. This finding confirms the isolation of research groups, which, operating in such a way, do not exploit the possibilities coming from the cross-fertilization among research areas.

As to the research methodologies, we found that the conceptual model is still the preferred approach on average across the research areas, even though the case study is generally preferred in "engineering" and "operation research and management science." Quantitative approaches relying on simulation are used to a limited extent only. Since conceptual models are mainly adopted at the beginning of a research topic, when conceptualizations and theories should be developed and are required most, this appears a strong limitation of the current literature. In fact, the number of theories developed on resilience in each research field still lacks

Table 4: Centrality measures for the citation network.

Node	Reference	Centrality measures				
		Betweenness	Out-degree	In-degree	Out-closeness	In-closeness
1	[35]	0	2	0	0.000406	0
2	[37]	0	1	0	0.000152	0
3	[38]	0	2	0	0.000406	0
4	[39]	0	1	0	0.000152	0
5	[42]	0	1	0	0.000152	0
6	[43]	0	4	0	0.000635	0
7	[47]	0	1	0	0.000152	0
8	[48]	0	1	0	0.000152	0
9	[51]	0	1	0	0.000203	0
10	[53]	1	1	1	0.000152	0.000152
11	[54]	0	1	0	0.000152	0
12	[56]	0	3	0	0.001551	0
13	[59]	0	1	0	0.000152	0
14	[60]	2	2	1	0.000305	0.000152
15	[62]	0	1	0	0.000203	0
16	[63]	0	1	0	0.000152	0
17	[64]	0	1	0	0.000152	0
18	[67]	0	0	1	0	0.000152
19	[68]	0	1	0	0.000152	0
20	[72]	0	3	0	0.00157	0
21	[79]	0	1	1	0.000152	0.000152
22	[80]	0	0	1	0	0.000203
23	[83]	0	2	0	0.001372	0
24	[84]	0	2	0	0.000499	0
25	[86]	0	1	0	0.000152	0
26	[88]	1	2	1	0.000381	0.000152
27	[89]	1	1	1	0.000152	0.000152
28	[91]	0	2	0	0.000406	0
29	[93]	0	0	1	0	0.000152
30	[94]	1	3	1	0.000457	0.000152
31	[96]	49.375	12	3	0.001967	0.000457
32	[98]	3.625	1	2	0.000274	0.000305
33	[99]	0	1	1	0.000274	0.000348
34	[100]	1	1	1	0.000152	0.000152
35	[104]	0	2	0	0.000305	0
36	[105]	0	0	1	0	0.000152
37	[106]	0	1	0	0.000152	0
38	[107]	6.410714	7	2	0.001106	0.000406
39	[108]	0	0	1	0	0.000152
40	[110]	2.410714	4	2	0.000697	0.000476
41	[112]	0	0	1	0	0.000203
42	[113]	1.910714	4	2	0.00061	0.000476
43	[14]	0	0	1	0	0.000203
44	[114]	0	0	4	0	0.00061
45	[115]	0	0	2	0	0.000305
46	[117]	5.410714	5	2	0.000897	0.000476
47	[118]	0	0	1	0	0.000152
48	[119]	4	4	1	0.000635	0.000152

Table 4: Continued.

Node	Reference	Centrality measures Betweenness	Out-degree	In-degree	Out-closeness	In-closeness
49	[121]	0	1	2	0.000152	0.000457
50	[122]	0	0	1	0	0.000203
51	[125]	0	5	0	0.00083	0
52	[131]	0	1	0	0.000152	0
53	[135]	17.91071	5	3	0.00083	0.000679
54	[136]	0	0	1	0	0.000152
55	[137]	0	1	0	0.000152	0
56	[138]	0	0	2	0	0.000305
57	[141]	6.5	3	2	0.000488	0.000549
58	[143]	0	1	2	0.000152	0.000542
59	[144]	0	0	1	0	0.000203
60	[149]	0	0	1	0	0.000152
61	[5]	9.535714	2	7	0.000305	0.001423
62	[150]	0	0	3	0	0.000488
63	[151]	0	0	2	0	0.000305
64	[153]	1	1	1	0.000152	0.000152
65	[154]	0	1	0	0.000152	0
66	[156]	1.410714	2	6	0.000305	0.001089
67	[158]	0	0	1	0	0.000203
68	[159]	0	3	0	0.000457	0
69	[160]	0	0	1	0	0.000348
70	[164]	0	1	0	0.000271	0
71	[166]	17.5	3	4	0.000457	0.000802
72	[167]	12	1	2	0.000274	0.000476
73	[168]	0	1	8	0.000152	0.001618
74	[171]	0	3	0	0.000488	0
75	[173]	9.5	2	2	0.000305	0.000498
76	[174]	0.5	1	1	0.000152	0.000152
77	[176]	0	0	1	0	0.000152
78	[178]	0	0	2	0	0.000636
79	[179]	0	0	17	0	0.002743
80	[180]	0	0	7	0	0.001487
81	[182]	0	0	1	0	0.000203
82	[183]	0	0	6	0	0.000844

operationalization and testing. This is especially true for the "environmental science and ecology" research area, which is the oldest one. Even though the numbers are still low, the adoption of simulation is, however, increasing, especially in "operation research and management science" and "computer science." This is a positive signal because simulation, introducing the possibility of reproducing system dynamics, can allow further drivers of resilience to be investigated from a dynamic perspective.

Based on these outcomes, our study contributes to the literature by suggesting some important directions for future research. First, as a general recommendation for researchers in all research areas, we suggest that collaboration among scholars belonging to different research groups, but within the same area, should be enhanced. This is recommended with reference to the performance of the "environmental science and ecology" research area, which is the one experiencing the highest growth in terms of number of papers and citations, and at the same time is the only one characterized by high collaboration among research groups. This would contribute to consolidate knowledge in each domain as to definitions, dimensions, attributes, and strategies to enhance resilience.

We also suggest that, given the considerable amount of conceptual research and the number of qualitative studies, more emphasis should be devoted to quantitative research approaches adopting, in particular, case studies and simulation. Both approaches would allow the attributes of resilience to be investigated in a greater depth and would contribute to the testing of the conceptual theories already developed

Table 5: Clusters from the citation analysis.

Cluster	Papers	Research areas
1	[14, 37, 43, 78, 93, 111, 112]	Engineering
2	[39, 148]	Engineering, psychology
3	[42, 58, 137]	Environmental science and ecology, engineering, business and economics
4	[5, 46, 61, 62, 88]	Engineering, operation research and management, computer science
5	[47, 92]	Environmental science and ecology
6	[50, 99, 136]	Environmental science and ecology, computer science, business and economics
7	[53, 117]	Environmental science and ecology
8	[63, 104]	Environmental science and ecology, engineering, computer science
9	[35, 59, 66, 79, 113]	Environmental science and ecology, engineering, operation research and management, computer science
10	[67, 107]	Engineering, operation research and management
11	[98, 175]	Environmental science and ecology, engineering
12	[38, 52, 121, 152, 157]	Engineering, operation research and management, psychology
13	All the other papers	Environmental science and ecology, engineering, computer science, business and economics

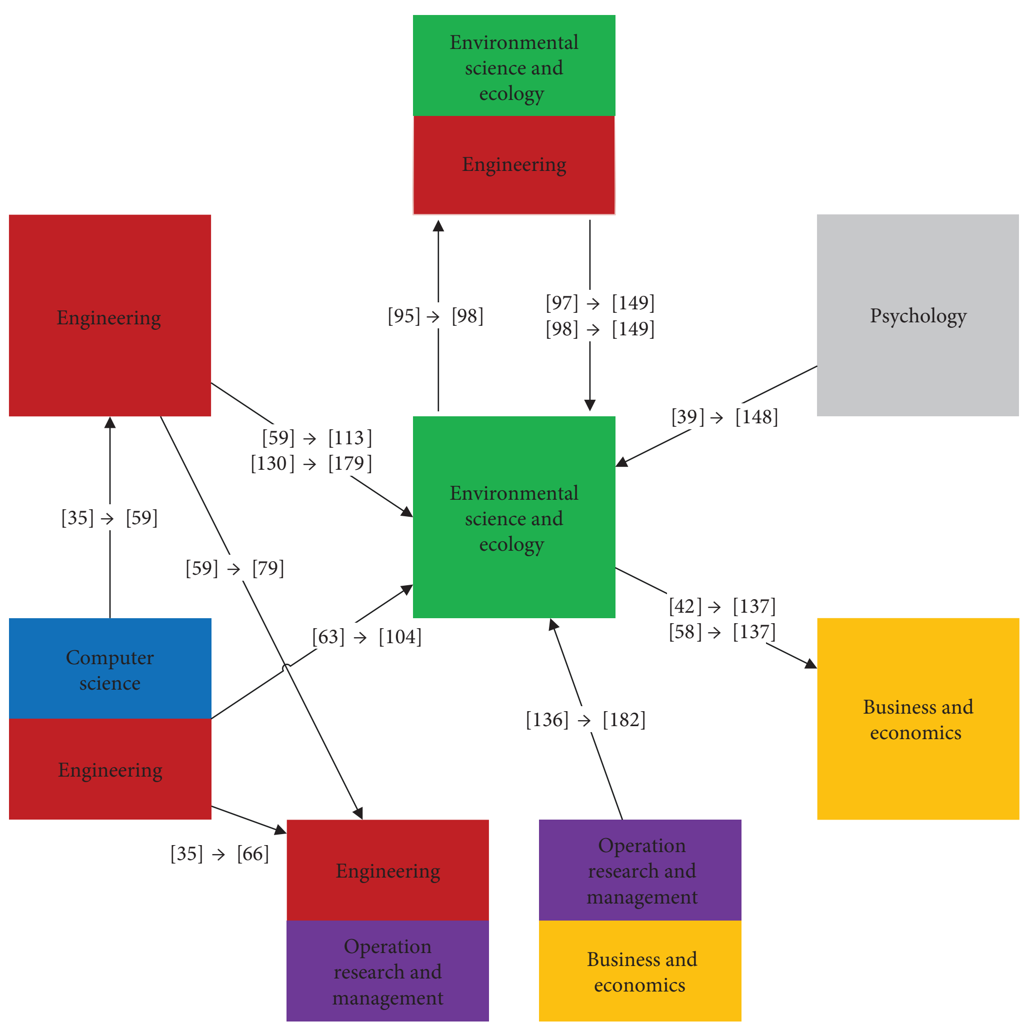


Figure 19: Citation relationships among research areas.

concerning them. This would allow the contradictory findings highlighted in the literature to be resolved, thus helping in identifying the boundary conditions of the theories. The case study approach is particularly useful because it could provide real examples and quantitative data to test the existing theories. Simulation could offer the possibility of testing and extending conceptual theories by adding new scenarios in a controlled laboratory setting.

Finally, we suggest increasing collaboration among researchers belonging to different areas. This should favor the exploitation of the results achieved in one area by scholars in another. At the same time, cross-field collaboration would encourage the exploration of new drivers of resilience, promoting development and creativity. To this aim, we suggest that the drivers investigated with reference to a given type of the complex system be contextualized to fit the features of other types of complex systems. This appears particularly promising for features concerning the governance of the system, which are proven to influence the resilience of business, economics, and supply networks. Similar variables could be identified, for example, for engineering and computer systems, and their effect on resilience could thus be tested.

Collaboration among different research fields is also useful to generalize resilience by integrating knowledge coming from different expertise and domains. In this regard, network theory can play a relevant role as a bridging theory. In fact, it is central in complex system analysis, and we found recent applications of network theory in studies belonging to multiple research areas (ecology, engineering, operation research and management science, computer science, and economics). Network theory can offer a common foundation to conceptualize complex systems, which can generally be framed in terms of nodes and links also at multiple scales (e.g., by modeling networks of networks or by employing multiplex networks). Furthermore, a network perspective can be adopted to characterize disturbances. From this point of view, rather than classifying disturbances based on the nature and/or intentionality of the event, they can be distinguished, in more general terms, focusing on the consequences. In doing so, disturbances can be classified as targeted on the node, link or network and operationalized as a partial or total removal of the node, link, or network, respectively. Network perspective can be particularly beneficial for investigating resilience in terms of robustness and vulnerability but also adaptive capacity, when disturbances targeted on the node, link, or network occur.

It provides a wide range of measures and complex tools to characterize the network topology and analyze network dynamics. This allows different types of complex systems to be compared across diverse research fields in a quantitative and objective manner. For this reason, it is particularly appropriate to analyses of the relationship between the topology of complex systems and resilience. Furthermore, network theory coupled with agent-based simulation is a promising tool for the investigation of the relationship between organizational and social features and resilience. Regarding this aspect, interesting applications refer to the degree of diffusion of trust and social norms within supply networks and social networks. By using diffusion algorithms, scholars may contribute to elucidating how these factors impact on the recovery and adaptation of these systems, a recent need of the literature.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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