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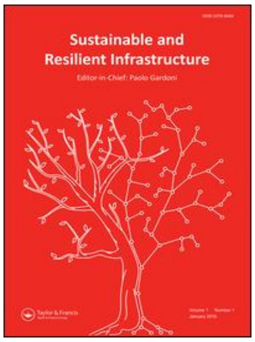

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Impacts of sustainability and resilience research on risk governance, management and education

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ABSTRACT
Substantial increase in research on sustainability and resilience is changing the traditional disciplinary boundaries of risk assessment and management. To understand the implications of this change and define future strategic directions for risk education, we conduct a comprehensive exploratory study of the knowledge domains encompassing risk, sustainability and resilience between 1990 and 2017. Combining quantitative bibliometric techniques such as term co-occurrence and bibliographic coupling, we show the historical evolution of the knowledge domains of risk, sustainability and resilience on a to-date unprecedented scale, based on 442,171 scientific records. Based on a comprehensive background study involving more than 100 cluster network maps, in the present paper, we illustrate the different disciplinary contributions, important authors, geographic distribution of the research, and the organizations producing the research as well as the extent to which they are integrated into the knowledge domain of risk. A complementary qualitative analysis provides context to the concepts and trends identified in the bibliometric analysis, together with an outlined vision for future education in risk, sustainability and resilience science.

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Risk-informed decision support; resilience; sustainability; risk education

1. Introduction

The challenges of the present and future societies are substantial. The list of specific issues that must be dealt with in the short, mid and long terms is breathtaking. Among others, they include how to best deal with poverty-related diseases, climate change, resource shortages, social unrest, immigration, disturbances of critical infrastructure services, interruptions of business lines, economic crises, events of natural hazards, etc. The challenge for societal developments at global scale may be summarized as: identify possible paths for sustainable developments and ensure that society develops in accordance with these.

The objective to meet this challenge comprises a moving and partly blurred target. This is because our knowledge on what constitutes and facilitates sustainability is both rather limited and at the same time continuously evolving. We have limited knowledge with respect to future natural hazard events which affects sustainability, and whereas we may direct prioritization of technological and organizational developments, we cannot with certainty predict the potential benefits and dis-benefits of these.

It is important to appreciate that the character of the global scale societal challenges outlined above is no different to any decision problem in society at smaller scales, whether in the context of industrial enterprises, public governance or private households; in the face of uncertainty and lack of knowledge, decision alternatives must be identified and ranked in accordance with their expected value of benefit (utility) with due account of limited budgets (e.g., money and resources) and possible constraints imposed by law and regulation, see e.g., Faber (2018, Routledge Handbook). The fundamental issue is that we need to be able to establish a basis for informed decision-making, accounting for our preferences for outcomes of different decision alternatives in full consistency with the best available knowledge – and we must act upon this decision basis. Sustainable developments at global scale depend on our ability to identify and decide rationally among possible relevant decision alternatives at lower scales.

The concept of risk as a measure to deal with and communicate the uncertainties associated with the outcomes of decisions has served to inform societal developments over many decades, see e.g., Hartford (2008). Especially over the last half-century, the concept of risk as a means for decision support has evolved to become an integral part of daily applied best practices in a very wide spectrum of industrial and governmental decision contexts (Soares, 2010). Numerous risk-based regulations of societal activities and frameworks for the

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management of natural disasters and accidents have been developed and implemented (e.g., ISO 2394, 2015; ISO 31010, 2009; ISO 31000, 2018). The utilization of the concept of risk in support of decision-making has significantly contributed to the development of civilization and welfare as we know it today. Nevertheless, as pointed out in Faber, Stewart and Faber (2011) there are several issues impeding the exploitation of its full potential. These include cognitive biases, inadequate and/or inconsistent representation of uncertainty and lack of knowledge, inappropriate criteria for risk acceptability and not least neglect of, or inapt risk communication; in the quest of sustainable societal developments we need to resolve these issues.

By now it is generally understood that the development of decision support for sustainable societal developments must take basis in a joint consideration of society, environment and economy – with due consideration of inter- and intra-generational equity, see e.g., Brundtland (1987), Solow (1991), Faber and Rackwitz (2004) and Faber (2018).

However, until now the developments of and utilization of the concept of risk as a means for informing decisions have been governed by the specific needs arising in different application areas and societal sectors. As a result of this, there is a detrimental variability in the understanding, applied terminology and best practice use of the concept of risk across different application domains. Moreover, this variability not only limits the full benefit of the risk concept within individual application domains but also seriously impairs consistency of decision bases and practical impact when decision contexts involving two or more application domains, as when addressing sustainability, are considered. There is thus a strong need to understand and utilize the concept of risk and risk-informed decision support in a fully holistic perspective where all aspects affecting sustainable societal developments are addressed not individually, not sequentially but jointly.

Moreover, especially over the last 2–3 decades, it is increasingly appreciated, that the management of systems, including engineered, social and ecological systems constitutes a capacity-demand management problem, which is greatly supported by the concept of systems resilience. This perspective not only adequately captures the essence of the challenge of sustainable societal developments at global scale but also greatly facilitates decision support at smaller scales. Whereas it might be stated that many of the aspects covered by the concept of systems resilience are already included in more traditional concepts, which have evolved within individual application domains, such as systems reliability, safety, availability, etc., the concept of resilience is holistic and envelopes the context from a perspective where the interaction between technical systems, the environment and organizations are in focus as basis for providing services supporting welfare and sustainable societal developments.

Based on the foregoing brief outline of developments related to the concept of risk as a means of providing decision support for developments in society we now take basis in the conjecture that risk-informed decision support, enhanced by the concept of systems resilience provides an adequate basis for the identification of sustainable paths for societal developments. A very substantial challenge in this connection is how to synthesize this conjecture and how to educate the next generation of researchers and societal decision makers.

The present study aims to bring order among the multiplicity of concepts and perspectives that join research and discourse on risk, resilience and sustainability. Our main objective with this is to develop a blueprint for a learning design that integrates these concepts. The analysis presented in this paper together with an accompanying comprehensive data report (Nielsen & Faber, 2018) aim to provide the basis for the learning design in terms of relevant subject expertise that future risk education should be built on.

The study combines quantitative bibliometric analysis techniques with an in-depth qualitative and critical literature review of emerging disciplinary fields, concepts, ideas and problems that unite as a result of integrating risk, resilience and sustainability. These methods are used in a complementary manner as an attempt to address methodological challenges individually associated with them. Bibliometric analysis is based on statistical data, which may not always capture nuances that a specialist in a given disciplinary area might, based on a working knowledge of the field. Qualitative literature reviews produced by disciplinary experts, on the other hand, have a number of drawbacks such as selection bias and potentially insufficient degree of representativeness, especially in broader disciplinary fields. A traditional literature review is usually aimed at an audience of peers in a given discipline, whereas bibliometric analysis allows newcomers or outsiders to a discipline to gain an overall intellectual structure of a given knowledge domain. Finally, information visualization techniques utilized in this study such as bibliometric science mapping are not only a showcase for the nexus between science, design and communication but also a didactic instrument, which fits well with the overall aim to establish an understanding of the system comprising the knowledge domain and thereby inform on future directions for both research education in the area of risk-informed decision support.

Sections 1 and 2 outline the aim, scope and background for the research. Section 3, together with the accompanying data report,[1] describes the methodology behind the two types of bibliometric analysis. Section 4 presents the results of the bibliometric analysis. Sections 5 and 6 include a qualitative review and analysis of developments, key concepts and trade-offs associated with sustainability and resilience and the potential for their integration in a common risk framework. Here too, bibliometric information and visualizations are used complementarily. Sections 7 and 8 discuss the impacts of integrating risk, resilience and sustainability for risk governance, risk management and risk education, concluding with recommendations for future direction of risk education.

2. Methodology for the bibliometric analysis

Bibliometric methods are statistical text mining techniques that can facilitate the mapping of scientific fields through discovering patterns in the evolution, structure and composition of large volumes of scientific literature. In the present study we use two such techniques – co-occurrence network of terms and bibliographic coupling – to visualize and analyze the knowledge domains of risk, sustainability and resilience for the period 1990–2017 based on 442,171 records extracted from the Web of Science (WoS).

Because risk, sustainability and resilience research do not constitute any particular scientific field but are studied as part of multiple fields in the natural, applied and social sciences, our approach encompasses the following steps:

(1) Identification of search terms relevant for risk, sustainability and resilience based on expert discussion between the authors;
(2) Data collection;
(3) Bibliometric networks construction;
(4) Data analysis, results and recommendations

2.1. Step I

In step I, we identified a total of 26 search terms relevant to the knowledge domains of risk, sustainability and resilience, which we further delineated into three groups (Table 1).

The search terms in Group 1 are the most general and contextually broad terms that refer to the knowledge domains of risk, sustainability and resilience as well as the combinations thereof. As research in the domain of risk has a significantly longer history and volume of scientific publications than that of either sustainability or resilience, we have split that into approximately three decades: 1990–2000, 2001–2010 and 2011–2017. Nomenclature in the risk domain is highly inconsistent in discriminating among aspects of risk research such as assessment, management or analysis. The use of these terms is strongly dependent on the sub-discipline undertaking research on risk. To be as comprehensive as possible, we designated our risk search term to encompass all three possibilities: Risk Assessment OR Risk Management OR Risk Analysis. We introduced further the three combinations Risk AND Sustainability, Risk AND Resilience and Risk AND Sustainability AND Resilience in order to facilitate analysis on the extent of mutual integration among them.

In Group 2 the search terms are chosen to represent the multi-disciplinary perspectives in which research on resilience is undertaken. There are three such more or less distinct contexts – Ecology, Engineering and Disaster research, however in addition to the overlaps among them, here too matters of taxonomy necessitated that we subdivide the ecology domain into Ecological resilience and Spatial Resilience; the engineering domain – into

Table 1. Expert-selected search terms.

Group 1 (knowledge domains)	Group 2 (multi-disciplinary perspectives)	Group 3 (concepts)
Risk 1990–2000	Ecological Resilience	Planetary Boundaries
Risk 2001–2010	Spatial Resilience	Natural Capital and Ecoservices
Risk 2011–2017	Engineering Resilience	Circular Economy
Sustainability	Infrastructure Resilience	Social OR Urban Metabolism
Resilience	Robustness	Inclusive Economy OR Inclusive Wealth OR Inclusive Growth
Risk AND Sustainability	Disaster Resilience	Degrowth
Risk AND Resilience	Community Resilience	Adaptive Governance
Risk AND Sustainability AND Resilience	Urban Resilience	Social Cohesion
	(economic) Development Resilience	Social Ecological Systems

Engineering Resilience, Infrastructure Resilience, and Robustness; and the Disaster domain – into Disaster Resilience, Community Resilience, Urban Resilience, and (Economic) Development Resilience.

The search terms in Group 3 are specific concepts that underpin the theoretical principles of the overarching risk, sustainability and resilience domains. The choice of search terms here was guided by the qualitative literature review and analysis performed prior to the bibliometric analysis and reflects the themes that emerged as trends in the evolution of risk research as a result of integrating sustainability and resilience considerations.

2.2. Step II

Based on the expert-identified search terms, we extracted a total of 442,171 records from the Web of Science (WoS) database. Only journal articles and book chapters were included. As a general rule, we excluded records which were categorized as part of medical research on risk as this very large sub-domain of risk research was not deemed of relevance to the scope of our study.

2.3. Step III

2.3.1. Term co-occurrence network visualizations

To provide a general overview of the significant topics related to risk, sustainability and resilience research, we constructed term maps using the VOSviewer software. VOSviewer is a text mining software based on the Apache OpenNLP toolkit, which performs part-of-speech tagging and uses a filter to identify noun phrases (terms), for which a relevance score is calculated. A low relevance score indicates that a term co-occurs with other terms following a more or less random pattern whereas a high relevance score is attributed to noun phrases that co-occur mainly with a limited set of other noun phrases (Van Eck & Waltman, 2014). Terms are derived from the titles and abstracts of the records downloaded from WoS. We have largely excluded terms with low relevance scores, which tend to be too general and non-context specific (e.g., 'conclusion', 'findings', 'originality value', 'future direction').

A network visualization is composed of terms and links. Terms are represented by their label and a circle. The size of a label and a circle depends on the number of publications that contain the term in the title or abstract. We have chosen the binary counting option in each map, which means that the number of times a term occurs in the title and abstract is of no significance, rather a term that occurs only once is treated in the same way as one that occurs multiple times. We set the minimum criteria for the inclusion of a term as follows: for 1–1000 publications at 10; 1000–5000 at 50; 5000–10,000 at 100; and above 10,000 at 200. This helps to deal with the problem of very large networks in a consistent manner.

Links are connections or relations between two terms. Each link has a strength, which depends on the number of publications where two terms occur together. The stronger the link, the thicker the line is in the visualization. Terms that co-occur often are located closer to each other whereas terms that have no or almost no co-occurrence are located farther apart. Terms are also grouped together into clusters. A cluster represents a set of terms strongly linked together. A term may belong to one cluster only. In the visualizations, a term has the same color as that of the cluster it belongs to. The clustering technique is based on an algorithm for solving an optimization problem and is discussed in detail in Waltman et al. (2010) and Waltman and van Eck (2013).

In most network visualizations, the clusters display a rather consistent representation of the multidisciplinary structure of a field and its subfields. In addition to the visualizations, we have provided tables listing the terms in their respective clusters, the number of occurrences of each term and the total strength of the links of a term with other terms. We use a color scheme in the tables to highlight (i) the significant concepts and notions related to risk, sustainability and resilience that are also discussed in their proper contexts in the qualitative analysis (blue color) and (ii) the appearance of the exact search terms identified during our expert discussion in Step I (red color).

2.3.2. Bibliographic coupling network visualizations

In a bibliographic coupling analysis the relatedness of items is based on the number of references they share: the larger the number of shared references, the stronger the bibliographic coupling is between them. In our study, we have chosen to represent the relatedness of three items: authors, countries and organizations. In each case, we have chosen the fractional counting method, which purposefully diminishes the importance of highly cited publications. This allows us to be inclusive of perspectives that are not bound by what passes as significant research based on citation numbers. The difference between full counting and fractional counting in technical terms is explained in detail in Van Eck and Waltman (2014).

We have chosen to display the bibliographic coupling of authors and organizations as density visualizations and the bibliographic coupling of countries as network visualizations mainly because the density format is clearer to read in the case of large networks but also because they help to visually identify knowledge hubs and subject experts at a glance. For all density visualizations, item density rather than cluster density is displayed. As with the network visualizations, items (authors and organizations) are represented by a label, whose size is indicative of its relative importance. The colors in the density visualizations range from blue to green to red, which reflects the density of terms at each point. The 'hot' red sections of the map indicate a large number of items in the neighborhood and high weights of the neighboring items. In contrast, the 'cold' blue sections represent neighborhoods with a small number of items and low weights of neighboring items. The technical implementation of the density visualization is discussed in Van Eck and Waltman (2014).

To create the bibliographic coupling network visualizations the same search terms and WoS records were used and a similar procedure was followed as that of the term co-occurrence. After uploading the data into the VOSviewer software and selecting the fractional counting options, a minimum number of (i) publications by author, (ii) publications by country, and (iii) publications by organization were chosen, adjusting that according to the number of publications we had available for each search term.

2.4. Step IV

The data results, analysis and recommendations are the focus of the present paper.

3. General observations

3.1. Historical evolution and growth rate of risk, sustainability and resilience research (1990–2017)

In Figure 1 the historical evolution of research in the domains of risk, sustainability and resilience is illustrated, showing the somewhat longer history of research in risk as well as the significantly larger volume of publications. While all three domains show an upward trend, sustainability and resilience research are still relatively marginal and only picking up from the mid-2000 decade.

In Figure 2 the total number of records on sustainability is compared with those that integrate risk and sustainability (orange) and those that integrate all three – risk, resilience and sustainability (grey).

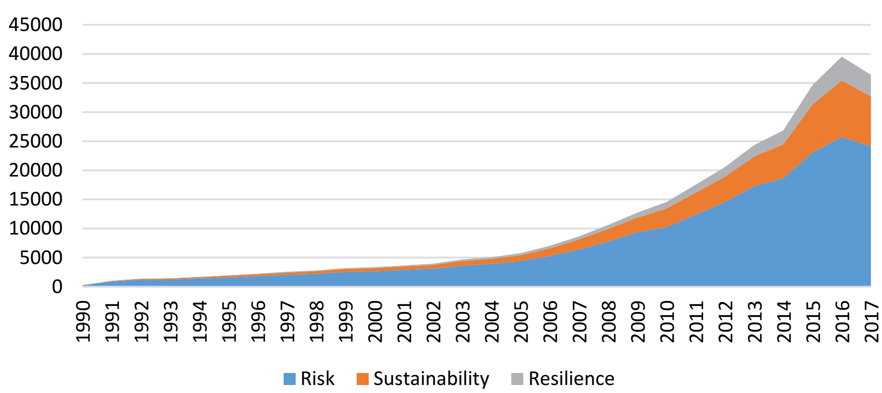

Figure 1. Evolution of research in the domains of risk, sustainability and resilience.

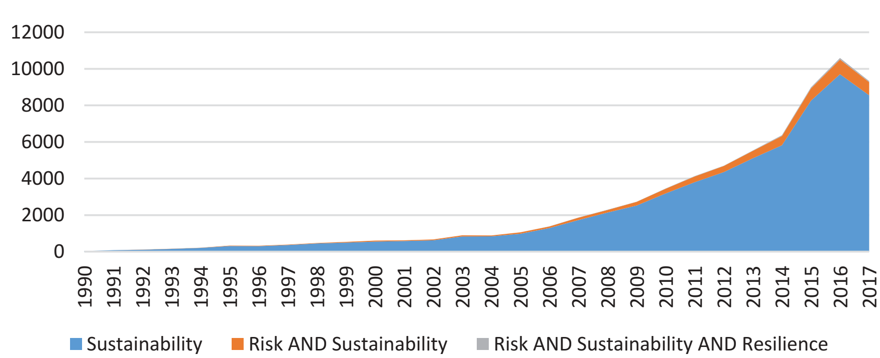

Figure 2. Integration of risk and resilience research into sustainability research.

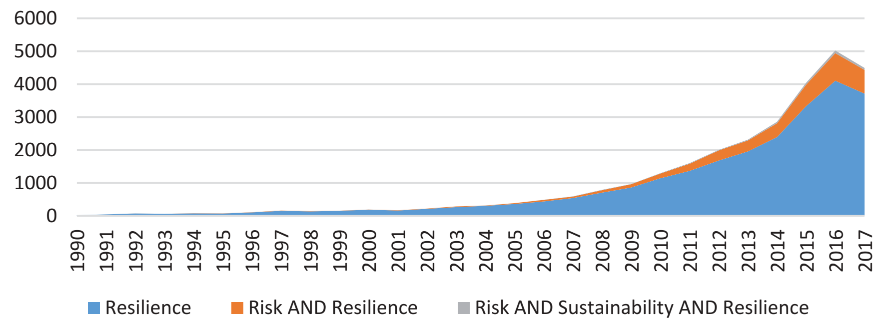

Figure 3. Integration of risk and sustainability research into resilience research.

Similarly, Figure 3 shows the evolution and volume of research on resilience, and the integration of risk and sustainability considerations in resilience research.

From these figures, we can conclude that risk is by far the dominant research field and that while some integration is visible between risk and sustainability and risk and resilience, research that integrates all three domains is at its infancy.

Finally, Figure 4 shows a selection from Group 3 terms. The birth and rapid growth of concepts such as circular economy, planetary boundaries, inclusivity, social cohesion, social-ecological systems, and adaptive governance can be seen as emerging all more or less simultaneously and growing at similar rates.

3.2. Multi-disciplinary composition of the risk, sustainability and resilience knowledge domains

In Figures 5–7 some examples of the distribution of disciplinary knowledge among the considered knowledge domains can be seen. First, looking at the general Group 1 terms – Risk, Sustainability and Resilience – we find that the Environmental Sciences and Ecology dominate all three. In the case of Risk, Engineering comes third, with only about 14% contribution and preceded by Public/Environmental/Occupational Health. This can be explained by the division between risk seen from a reliability or a safety perspective. If the reliability and safety perspectives are combined, the Environmental Sciences come second.

In general, for all the 26 terms it could be said that the top three contributing disciplines are Environmental Sciences, Engineering and Economics – mostly in that order, with some minor exceptions. We interpret this as approximating the three systems perspectives: ecological, engineered and social systems. In the case of social systems, we interpret Economics to be the principal discipline (theoretically and methodologically) contributing to research on risk, sustainability and resilience in social systems. Other Social Science or Humanities disciplines are either non-present or extremely marginal.

The leadership of Environmental Sciences and Ecology becomes even more pronounced at the level of Group 3 – specific concepts, where a large number of these concepts are almost entirely dominated by the environmental/ecological perspective, e.g., adaptive governance, social ecological systems, planetary boundaries (Figures 8–11). It is possible to argue that such concepts are then vulnerable to ideology as well as non-intentional, cognitive biases. A somewhat better balance

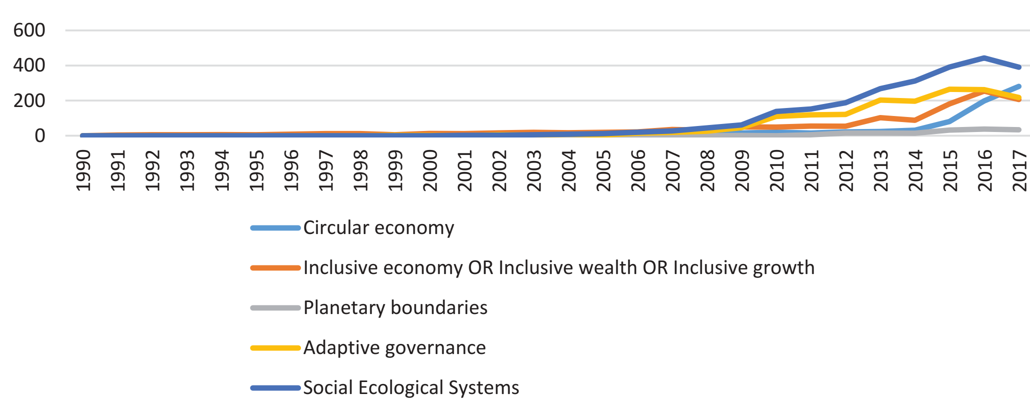

Figure 4. Evolution of research on the concepts of circular economy, inclusive economy/wealth/growth, planetary boundaries, adaptive governance, and social ecological systems.

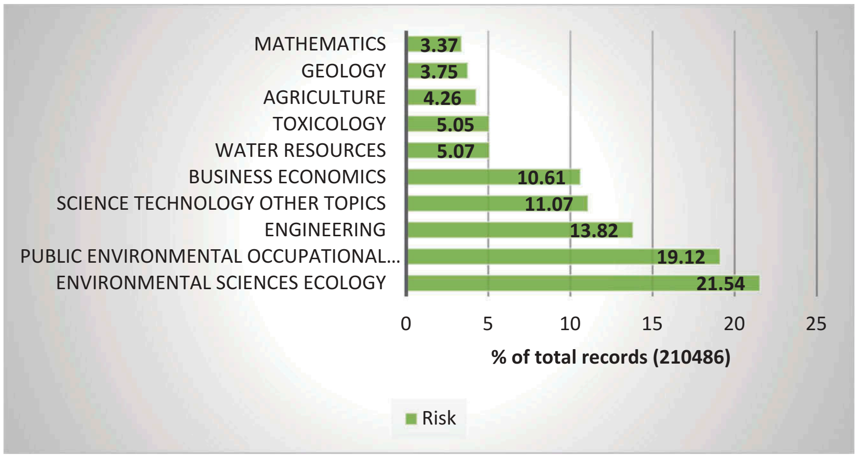

Figure 5. Disciplinary composition for the knowledge domain of risk.

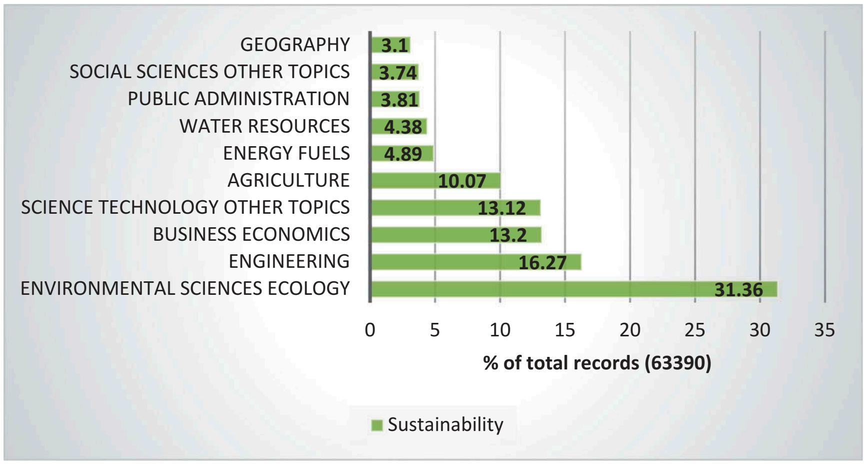

Figure 6. Disciplinary composition for the knowledge domain of sustainability.

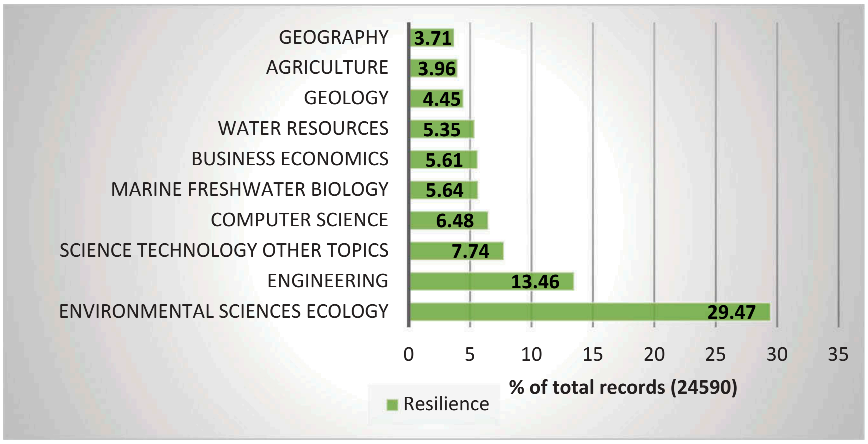

Figure 7. Disciplinary composition for the knowledge domain of resilience.

can be seen in the case of circular economy. The construct social-ecological systems are also interesting from the point of view that here too actual social science research is extremely marginal (Sociology 3%, Geography 8%, Public Administration 5%) in comparison to its hyphened counterpart (Ecology 73%).

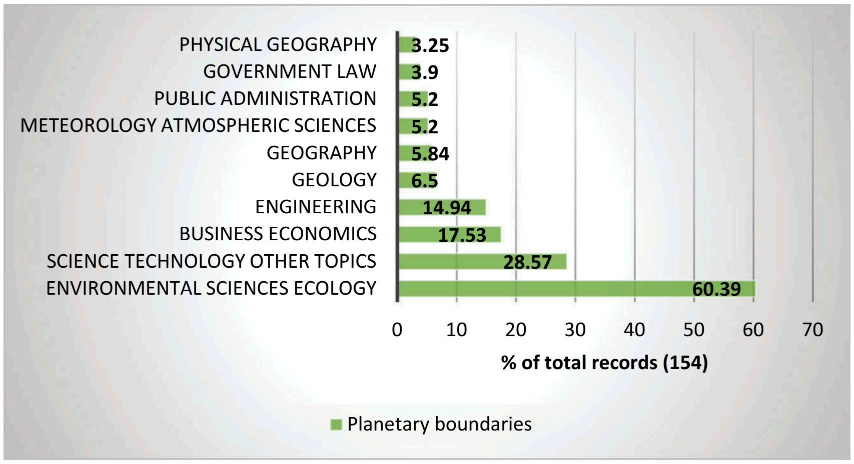

Figure 8. Disciplinary research on the concept of planetary boundaries.

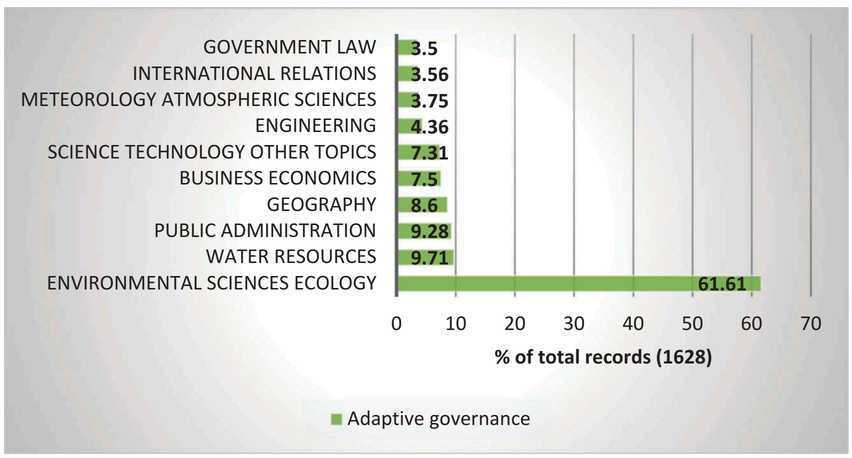

Figure 9. Disciplinary research on the concept of adaptive governance.

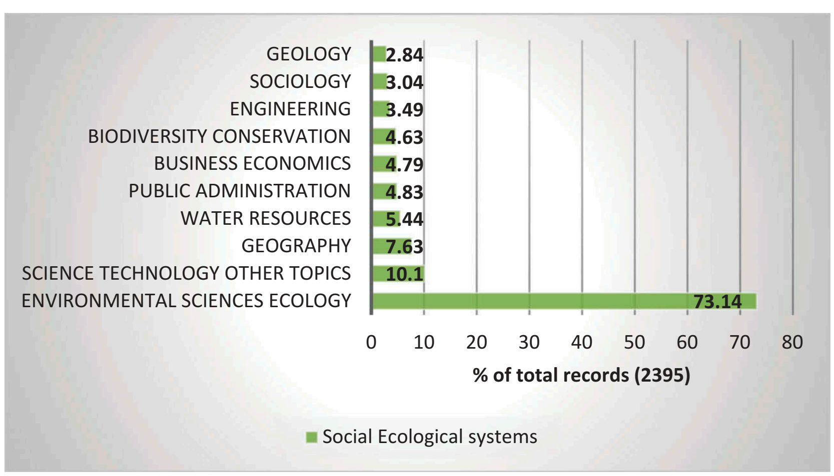

Figure 10. Disciplinary research on the concept of social ecological systems.

As the authors' perspective stems from the context of Engineering decision-making, the contribution of research from the domain of Engineering to all identified terms are shown and compared to the other two dominant knowledge domains: Environment/Ecology and Economics (Figure 12). Unsurprisingly, research on Robustness, Engineering and Infrastructure Resilience is heavily dominated by the Engineering

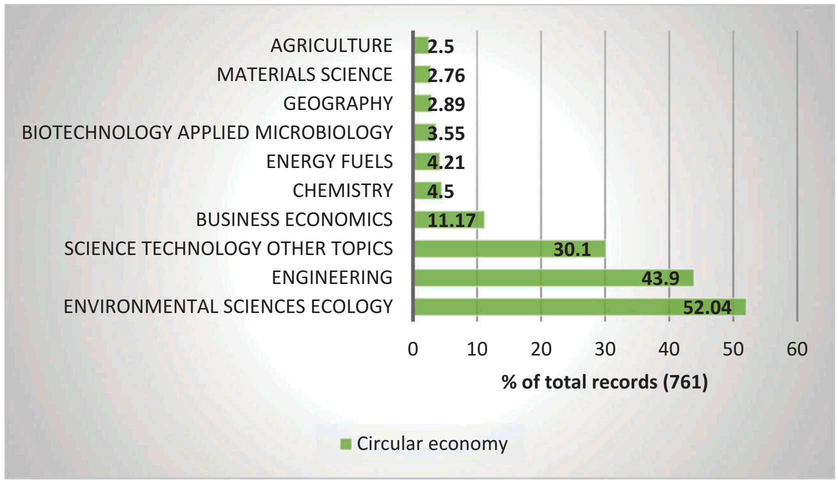

Figure 11. Disciplinary research on the concept of circular economy.

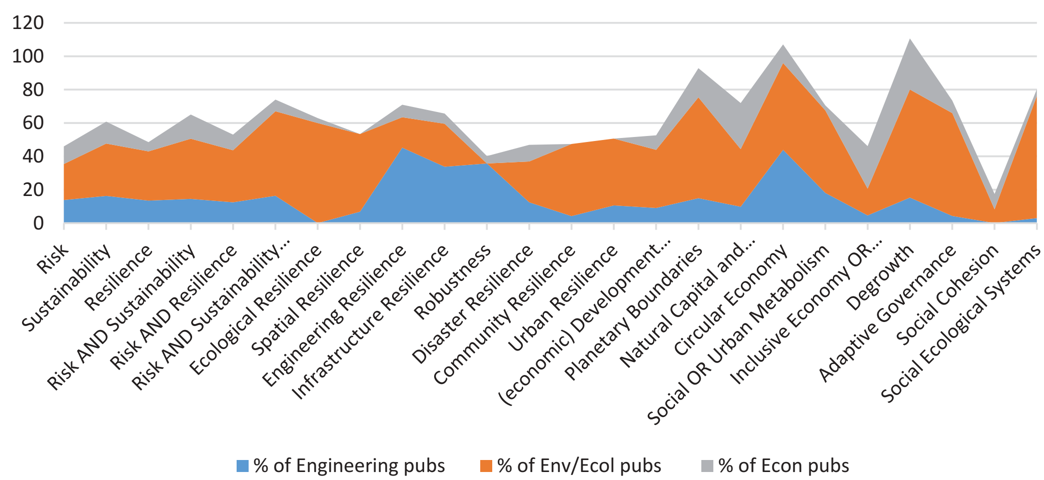

Figure 12. Contribution of research from the Engineering knowledge domain to all expert selected search terms.

disciplines. Figure 12 also shows that Engineering research is a large part in what we believe represents the quantitative sustainability dimension, i.e., circular economy and related concept of urban/social metabolism.

With regard to research in Resilience, the contribution shows a consistent trend at about 15%, making Engineering the second largest contributor. Interestingly, research dominated by the disciplinary field of Ecological Economics shows the same constant percentage, e.g., planetary boundaries, degrowth and ecoservices. Engineering is missing or is very marginal in the Social domains, e.g., social ecological systems, social cohesion, adaptive governance, and all the community-related aspects of resilience.

3.3. *Term co-occurrence analysis results*

In this section, we look at some examples of the term maps we developed to represent knowledge domain clusters and relations among them. These visualizations we believe facilitate the apprehension at a glance the multi-disciplinarity of many of the concepts (expressed as the number of clusters) as well as the trans-disciplinarity among them (expressed as link strength and distance among individual nodes and clusters). It goes without saying that interpreting these maps has a strong element of subjectivity, but we believe they are an efficient visualization tool that allows a quick screening of trends and patterns in a vast amount of data that can be used to direct further more detailed analysis.

Figure 13(a–c) represents the development of research in risk over the past three decades. The split was necessary due to the very large number of records (over 200,000), which the software could not process in one batch. In the first decade of Risk (Figure 13(a)) we see four clusters – the largest (red) is clearly identified as belonging to the decision-theoretic knowledge domain, with terms like

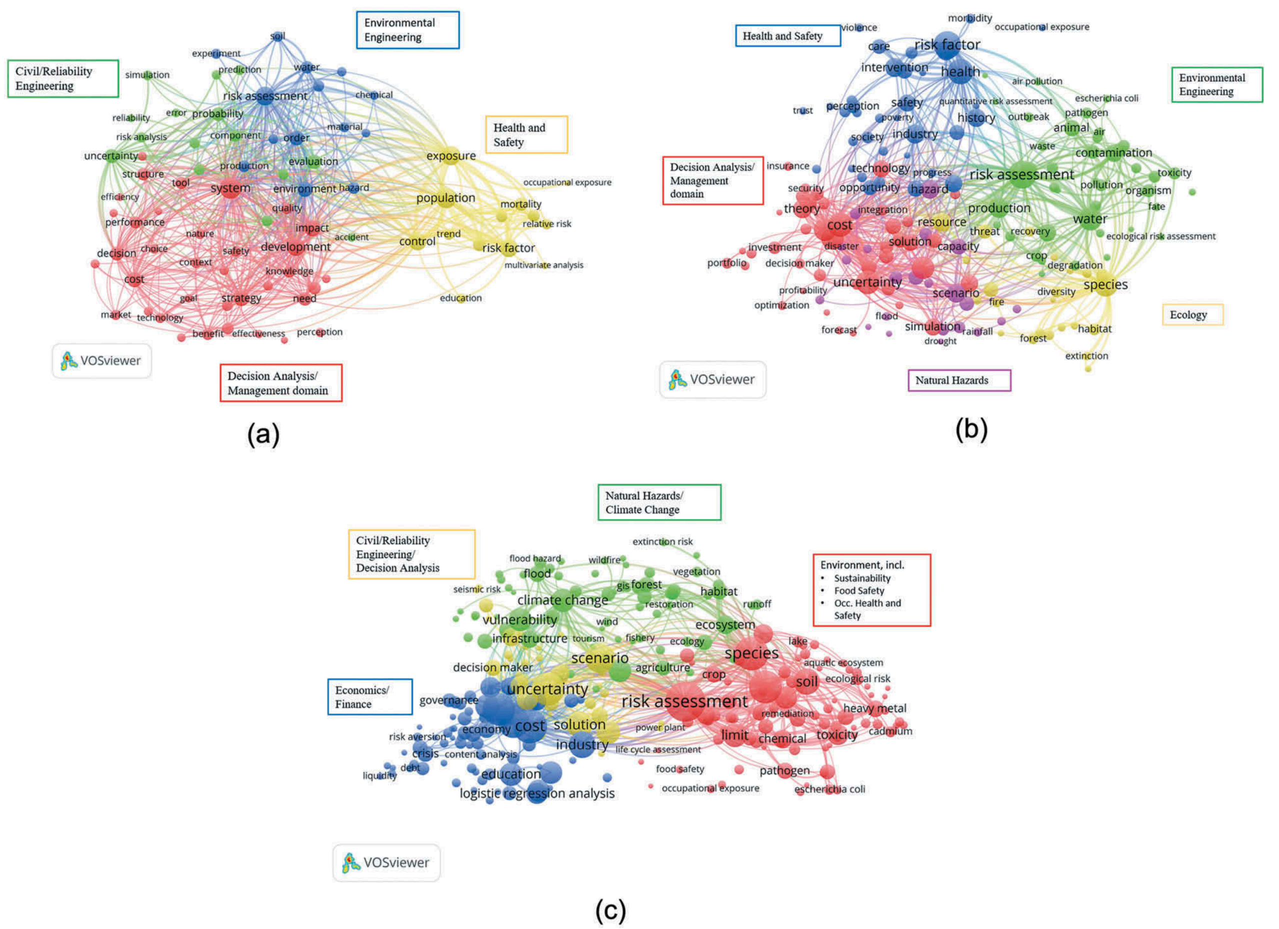

Figure 13. (a) Network map of research in the domain of risk 1990–2000. (b) Network map of research in the domain of risk 2001–2010. (c) Network map of research in the domain of risk 2011–2017.

choice, decision, alternative, efficiency, performance, solution, utility, etc. Closely related are the green cluster of Civil/Reliability Engineering (e.g., uncertainty, probability, reliability, risk analysis) and the blue cluster of Environmental Engineering (e.g., chemical, water, soil, environmental hazard). Rather distant from these three clusters, the yellow cluster is the human domain of Health and Safety (e.g., occupational exposure, mortality, population).

In the second decade of Risk (Figure 13(b)), decision theory/analysis is still the dominant cluster (red). The Environmental Engineering perspective is still clearly visible (green). Health and Safety (blue cluster) seems to have grown in size as well as come closer to the environmental and decision domains. There is no immediately visible sign of Civil Engineering, which seems to have been incorporated into the decision cluster (e.g., uncertainty, forecast, solution, optimization). Here within the red cluster we also see the emergence of a new cluster (pink), highly integrated into the red – it is the natural hazards domain from the perspective of engineering (e.g., drought, hazard, scenario, rainfall). We interpret this to mean that the two principal interests in Risk from the Civil Engineering discipline during 2001–2010 were incorporating decision analysis for optimization problems and natural hazards.

A new knowledge domain has also sprung from or in close relation to the Environmental Engineering perspective, namely the yellow cluster, which we consider to be the Ecology domain (e.g., species, diversity, resource, threat, extinction, degradation).

Moving to the current decade, starting 2011 (Figure 13(c)), the shift in risk research toward environment becomes even more pronounced. Here we see the dominant red cluster is the Environmental risk cluster, where elements of quantitative sustainability have also found home (e.g., life cycle assessment) but also the hybrid area of food safety and security (food safety, pathogen, escherichia coli), and oddly enough health and safety (occupational exposure), which has been reduced from a big cluster in the previous decade to a minor node in the environment cluster.

The next big cluster (green) could be seen as a particular aspect of the environmental one – here we have the natural hazards, grouped together with climate change. Economics and finance (blue cluster) sits rather far from both the Environment and Climate. The decision theoretical and Civil Engineering perspectives are here united in the middle yellow cluster. Although the smallest cluster, it has now centrality in the network with strong links to Economy and Climate change and Natural Hazards domain and somewhat less so with Environment.

From comparing the maps for the three decades of risk, we conclude that risk research has evolved from being

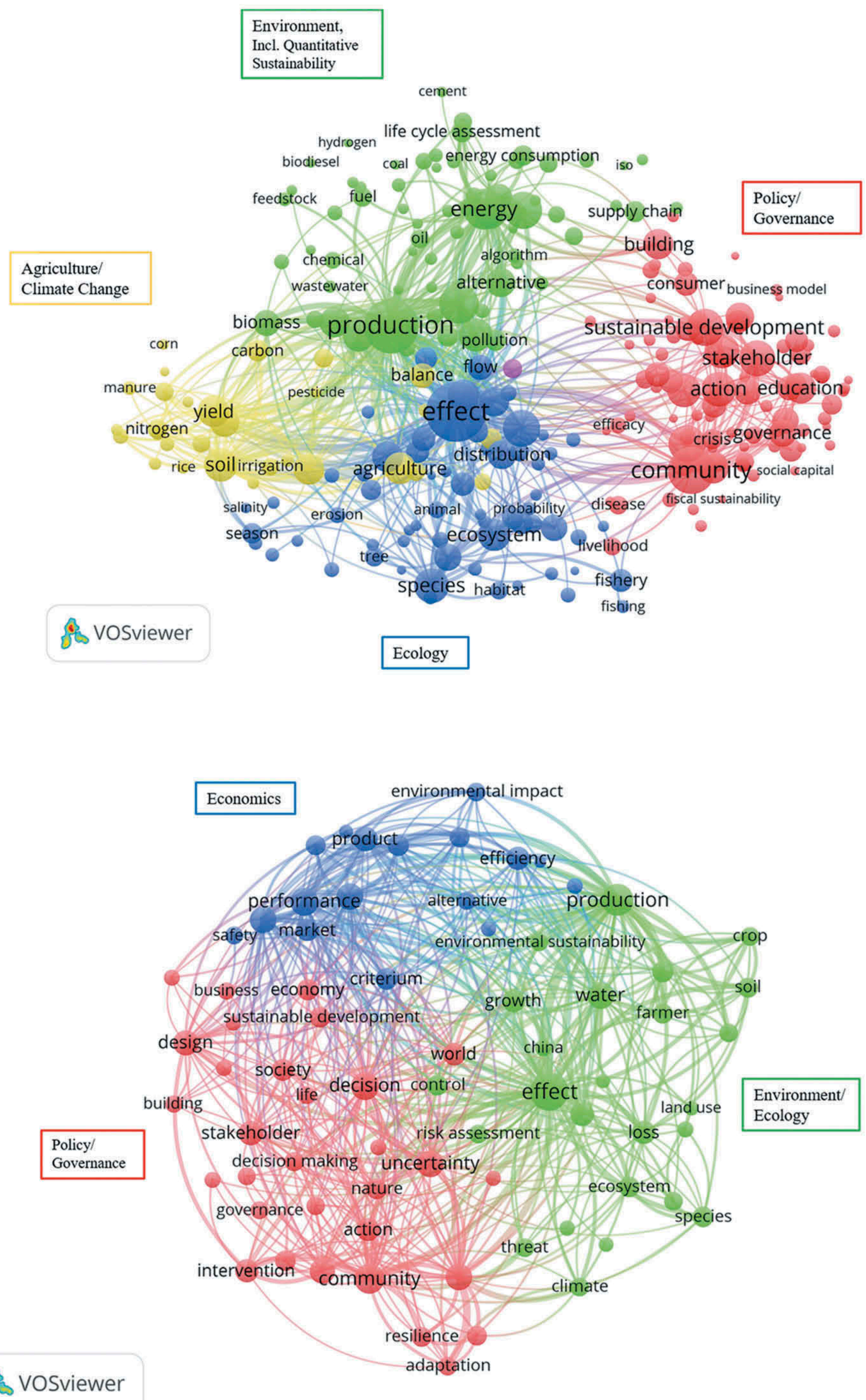

Figure 14. Network map of research in the domain of sustainability. (a) Network map of research combining the domains of risk and sustainability.

strongly dominated by a decision theoretical and civil engineering perspective in the 1990s toward a dominant Environmental/Ecological paradigm. We see the waning significance of areas such as Occupational Health and Safety and the introduction of new ones such as Food Safety, Climate Change and Natural Hazards. While it might seem that the trend in the environmental perspective replacing the engineering perspective is bad news for engineers, we argue that the relative positioning of the engineering perspective in the center of the map depicting the current decade is a favorable opportunity for the engineering knowledge domain to play a central and unifying role among the various disciplines contributing to risk research. From this point of view, a criteria for success would be the manifestation of integration between risk, sustainability and resilience on different levels – in research, in management/practice, and crucially, in education.

In what follows, we analyze a selection of maps related to sustainability and resilience.

In Figure 14 an all-inclusive map of Sustainability is given. There are four distinct clusters. The single pink node in the middle stands for Resistance. We have decided to integrate it into the blue cluster, which is the Ecological perspective cluster as the idea of Resistance is closely associated with Ecological Resilience. The dominant cluster is the red one – we label it the Policy/Governance perspective (e.g., accountability, action, credibility, ecological footprint, capacity building, inequality, stakeholder, transparency). We notice also that this dominant cluster is where all the social/societal systems' terms are located (social capital, livelihood, identity, leadership, education, empowerment). This cluster also stands rather distinctly apart from the natural science domains that are represented in the other three clusters. This shows a rather clear division between the natural and social sciences producing research on Sustainability. The green cluster represents the Environmental perspective, from the point of quantitative sustainability (e.g., life cycle assessment). The blue cluster represents the Ecological perspective (e.g., ecosystem, species). The yellow cluster belongs to Agriculture in combination with Climate Change (e.g., soil, irrigation, pesticide).

Comparing the general map of Sustainability to the more specific one that combines Risk and Sustainability (Figure 14(a)), we observe that the number of clusters has been reduced and that the whole network has become more dense. In contrast to the map in Figure 14 there are no particular dominating single nodes such as action, community, sustainable development, effect, energy, etc. We identify such nodes with largely ideological content or policy buzzwords that do not characterize any particular research discipline but are used as a political instrument to promote any given research. In this respect, we have identified a number of knowledge domains, which are almost entirely dominated by words lacking any specific content (e.g., Inclusive Economy/Wealth/Growth, Urban/Social Metabolism, Degrowth, and Social Ecological Systems). Maps and all meta-information of the maps can be found in the data report.

There appears to be less ideology in the map in Figure 14(a). There the dominant cluster is the red one. We see it as a mesh-up of Decision Analysis, Civil Engineering, Risk Management and Risk Governance. We could also call it the Policy domain as it is less about assessment than about management (e.g., decision-making, evidence, governance, risk management, resilience, uncertainty, stakeholder, vulnerability, action, adaptation). The green cluster is the Environmental and Ecological perspectives combined (ecosystem, landuse, species, threat, climate, effect, crop). The small blue cluster is Economics (performance, market, efficiency, product). Altogether, these three clusters represent the three pillars of sustainability: ecological, social and economic.

Unlike Sustainability, which lost two clusters in the specific risk and sustainability consideration, for Resilience, the opposite is visible. The map of Resilience (Figure 15) shows two very distinct clusters located far from each other. There is a one node outlier (the blue dot), which stands for Redundancy, so we have added it to the green (Ecology) cluster. It is clear that the green cluster is very dense, with terms closely and strongly related to each other. This we argue is the case because Ecology as a discipline is rather homogeneous. There is not much multi-disciplinarity present here even though it is typically authors from the Ecological domain who are the most pronounced advocates of multi and trans-disciplinarity as exemplified by the constructed concept of social-ecological systems.

The distant and weakly related red cluster is composed of many loosely and weakly related nodes. It is the melting pot of just about any discipline that has adopted the term Resilience – for scientific or political purposes or both. Here we see, risk, civil engineering, natural disasters, food security, policy and governance, a bit of economics, a bit of psychology and education. Unsurprisingly, many of these are loose ends and stand as single nodes in the cluster. Links among the nodes in this cluster are weak as are the external links connecting the Ecology cluster.

In the map in Figure 15(a) risk meets resilience in three closely related clusters. It is, in fact, a map of the three dominant perspectives of resilience, which we have identified in Group 2 search terms. The dominant red

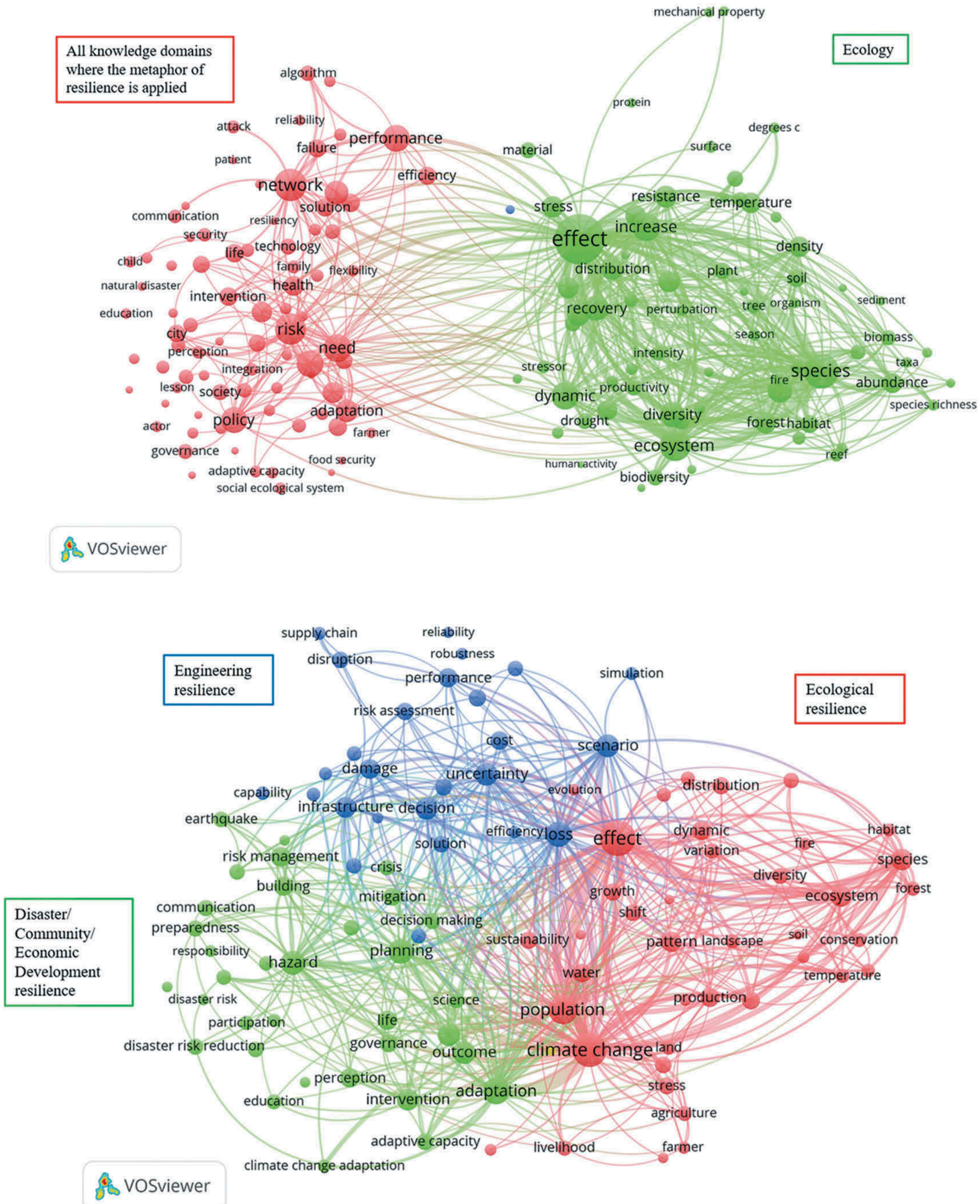

Figure 15. Network map of research in the domain of resilience. (a) Network map of research combining the domains of risk and resilience.

cluster is the Ecological Resilience Cluster (e.g., diversity, ecosystem, growth, shift, population, production). The blue cluster is the Engineering Resilience cluster (e.g., infrastructure, robustness, risk assessment, scenario, damage, performance, reliability, decision, uncertainty). The green cluster is the Disaster/Community/Urban and (economic) Development cluster (e.g., hazard, mitigation, preparedness, adaptive capacity).

The first thing that happens when we add Sustainability and Resilience to Risk is that the number of records drops from 140,000 + to fewer than 400. So is this smaller universe also qualitatively different?

In Figure 16 the dominant cluster is the red one, though it should be noted that it is not as dense as the green cluster. The red cluster here is a combination of the Decision theoretical, Civil Engineering and Policy perspectives (hazard, exposure, loss, reliability, performance, robustness, recovery, effectiveness, etc.) In this cluster, we clearly see the Engineering perspective of risk-informed decision support.

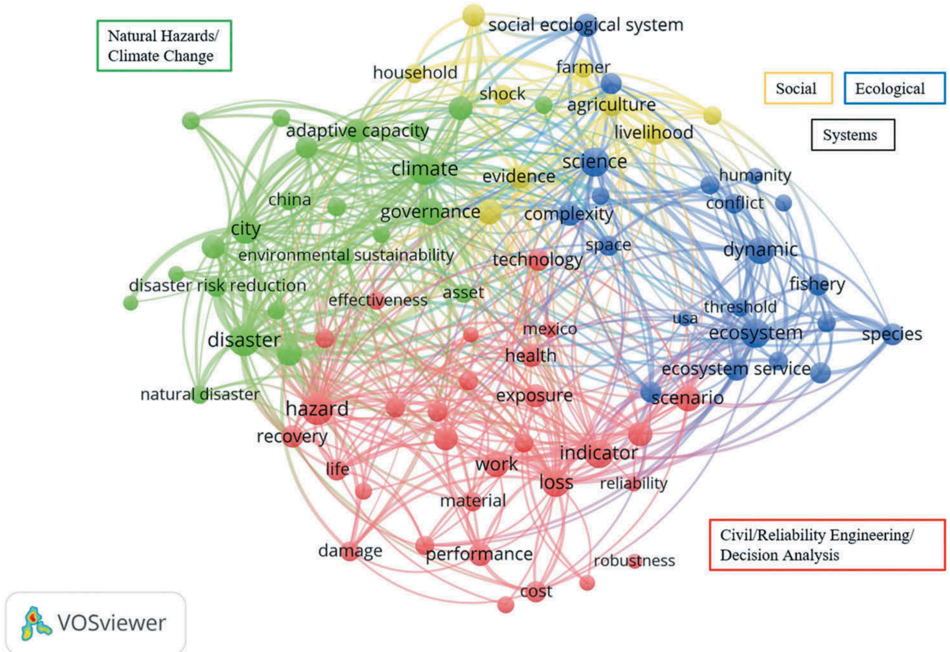

Figure 16. Network map of research combining the domains of risk, sustainability, and resilience.

The closely positioned and denser green cluster is the Natural Hazards and Climate Change domain. The blue and yellow clusters are the social ecological systems domain, where the former is represented through terms like agriculture, livelihood, household, farmer, etc., and the latter by ecosystem, ecosystem service, complexity, threshold, humanity. It should be noted that while the social domain seems to be exemplified by individual entities (household, farmer), the ecological one deals with collective ones (humanity, system, species). The emphasis on the individual in the context of social systems is possibly due to the dominance of Economics and Psychology to account for various types of individual human behavior. It is also evidence for the complete lack of e.g., Anthropological/Cultural research on risk that would account for aspects of collective human behavior. It is only when we look closer at the particular Group 3 terms, where the concept of Social Cohesion is the single case where collective human behavior becomes of concern to risk and resilience.

We conclude from this map that research integrating the three concepts is largely driven by the risk perspective, and more specifically, that of Decision theory/Civil Engineering. This confirms our previous conclusion that the centrality of the Engineering perspective (Figure 13(c)) should be interpreted as an opportunity for the engineering knowledge domain to play a central and unifying role among risk, sustainability and resilience research.

A more radical conclusion is that although the Ecological perspective is the one lobbying for the unification of representing and assessing social and ecological systems jointly, i.e., *Social Ecological Systems*, it appears that no such unification is actually happening in research or in real life. The domain of the 'natural environment' is clusters away from the domain of humans. It appears however that a stronger link can be made between the social and the engineered systems as we see in a number of maps where the social and the engineering terms are often located within the same cluster.

3.4. Bibliographic coupling analysis: distribution of knowledge in risk, resilience and sustainability by countries and organizations

We now turn to the last sample results of our analysis – the bibliographic coupling analysis, where we look at the distribution of knowledge in risk, resilience and sustainability by country and organization. (See also bibliographic maps for all terms in this document in the data report. The data report includes also an additional category – 'author', which facilitates the observation of the relatedness of expert communities or the fragmentation of research.)

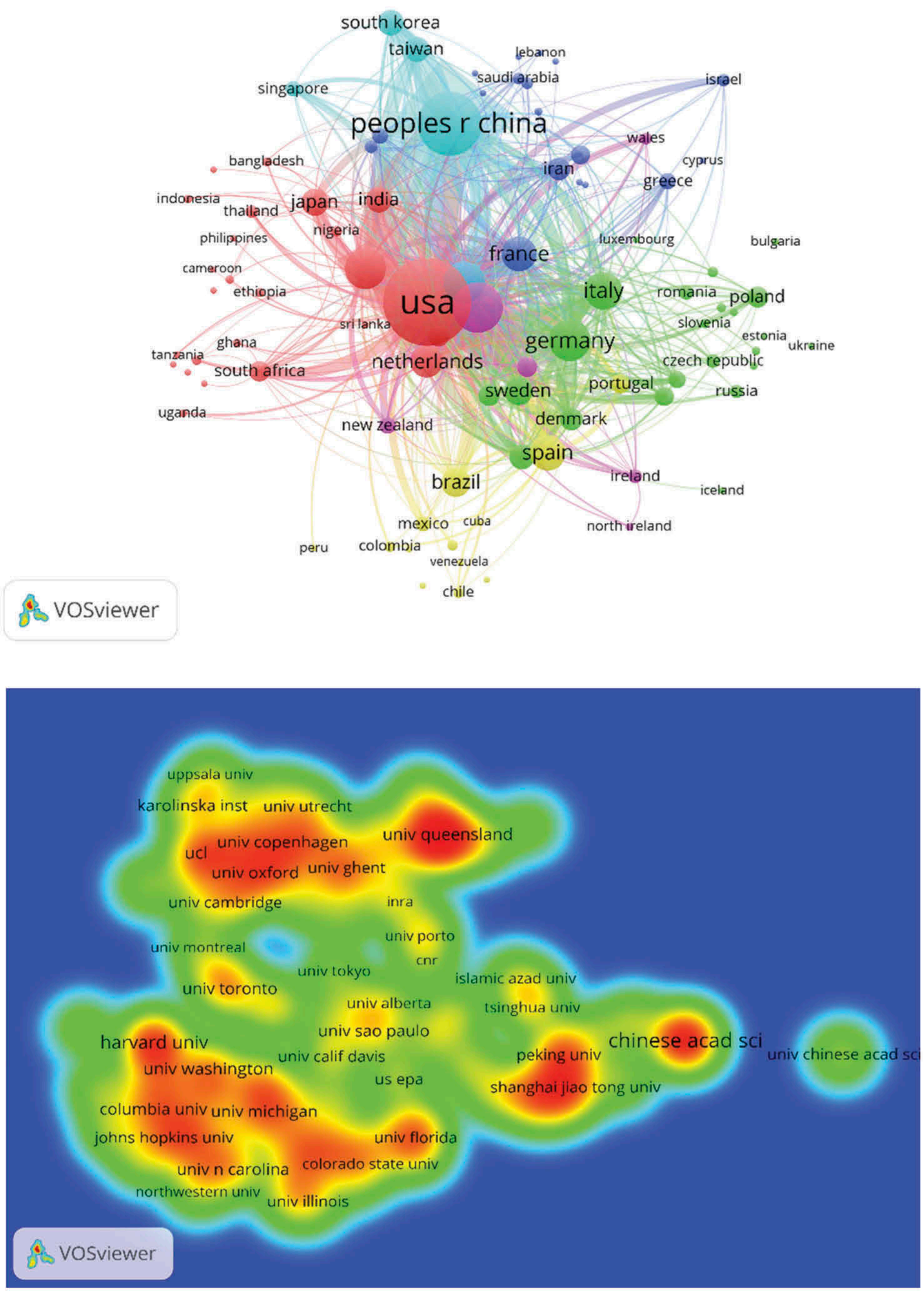

Figure 17. Geographic distribution of research in the domain of risk 2011–2017. (a) Organizational distribution of research in the domain of risk 2011–2017.

In Figure 17, the last decade of Risk research is shown, where the two dominant producers of research are the USA and China, though the exchange between them is relatively week. In the green cluster are located continental and Scandinavian European countries, with Germany and Italy having the lead and to some extent Sweden and Denmark. Eastern and Central European countries are also part of this group, though with lesser contribution and weaker ties to the others and themselves. The yellow cluster we call the Latin cluster, with Spain, Brazil and Portugal having the lead. The red cluster dominated by the US is also where we see strong relations between the latter and Japan, India, the Netherlands, some African countries and some southeast Asian countries. The pink cluster belongs to the Commonwealth countries (except India) – The U.K., Australia, Canada, New Zealand. The

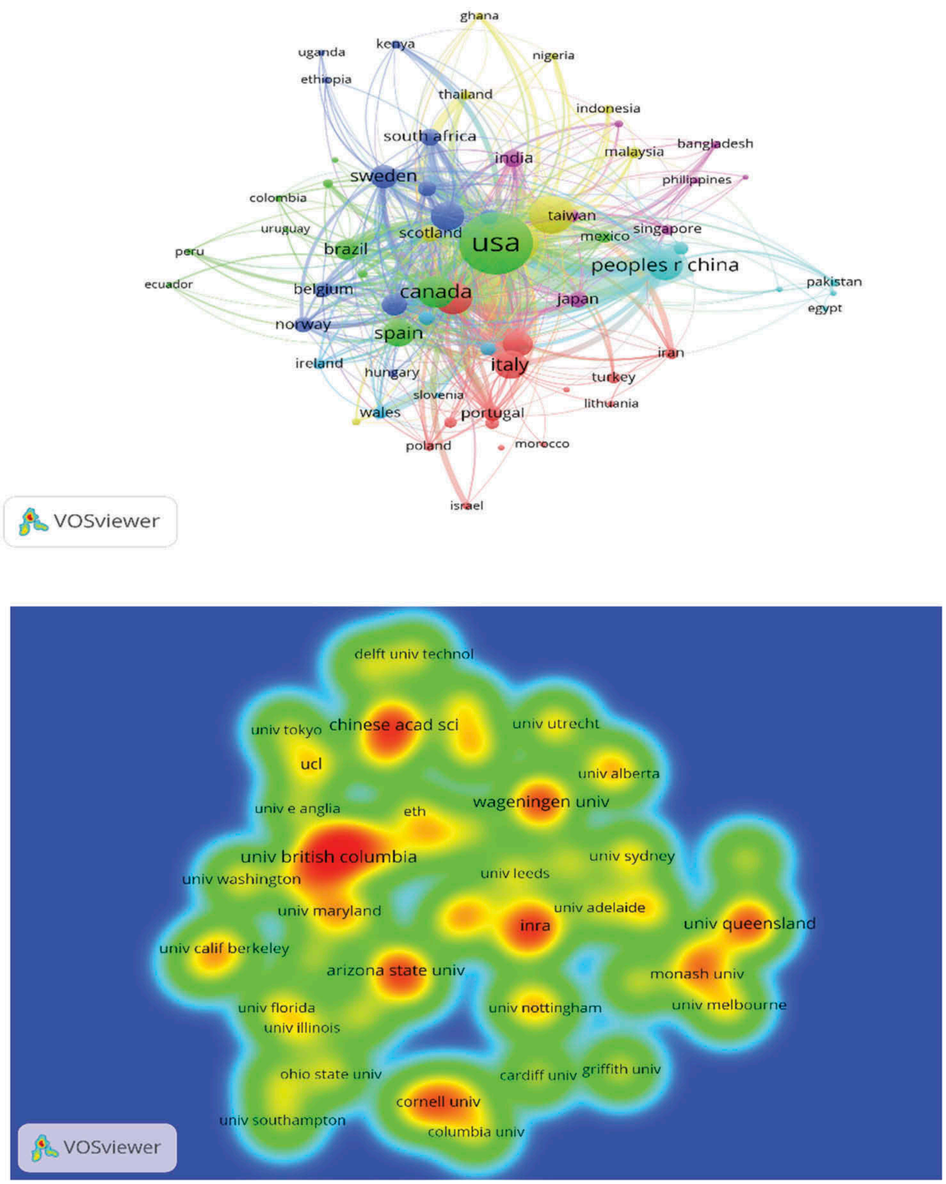

Figure 18. Geographic distribution of research combining risk and sustainability. (a) Organizational distribution of research combining risk and sustainability.

light blue is China and neighbors – South Korea, Singapore and Taiwan. The dark blue is dominated by France and Iran.

So apart from the obvious linguistic patterns that seem to be at work, we could see that exchanges are also based on historical geopolitical relations between countries and spheres of influence. Looking at the map of organizations (Figure 17(a)), we can see a distinct North American knowledge hub in the bottom left, where the main actors are Harvard, Columbia, University of Michigan, University of Washington, Colorado State University, etc. To the right are two Chinese hubs: Peking and Shanghai Jiao Tong universities in close collaboration and the Chinese Academy of Sciences. At the top, a relation is observable between the European hub (Oxford, Ghent, UCL and Copenhagen) and the Australian (University of Queensland).

Less obvious to describe patterns is the country map for Risk AND Sustainability (Figure 18). Here we see the dominant countries USA, China, Canada, Scotland, Spain, Italy, Sweden and Brazil, but we do not see any particular linguistic or historical patterns that might be influencing the exchanges.

The organizations map (Figure 18(a)) looks a lot more fragmented than that of Risk, with many small hubs spread around. The biggest one is UBC in Canada, the Chinese Academy of Sciences, Wageningen in the Netherlands, and

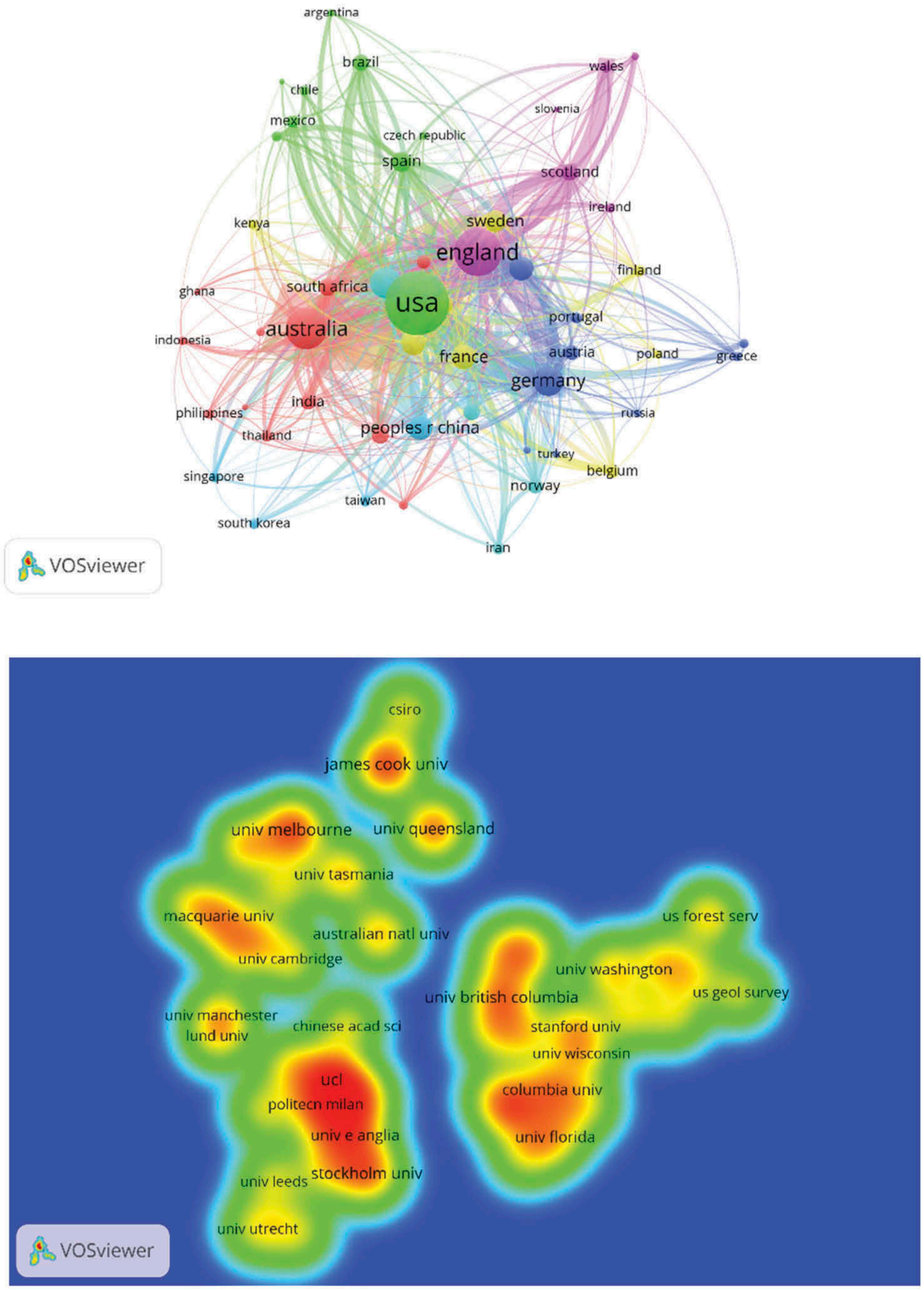

Figure 19. Geographic distribution of research combining risk and resilience. (a) Organizational distribution of research combining risk and resilience.

a trio from Australia: University of Queensland, Monash and University of Melbourne.

Research on Risk and Resilience is largely dominated by what we could call the Anglo-Saxon group: USA, The UK, Australia and Canada (Figure 19). Unlike Risk and Sustainability, China is not a major producer of research. Other important countries are Germany, Sweden and Scotland.

Looking at the organizations map, no doubt the Stockholm Resilience Center is in the hottest area of the map, together with collaborating institutions in the UK and Italy – UCL, Milan Polytechnic and University of East Anglia. (Figure 19(a)). Australia has several small hubs around James Cook University, Melbourne and Queensland. We see also a UK-Australian hub represented by University of Cambridge and Macquarie University in Sidney and a UK – Swedish connection between University of Manchester and Lund University. On the right side of the map is the North American hub represented by University of British Columbia, Canada and a number of US institutions, most prominent of which is Columbia University.

4. Emerging perspectives and concepts

4.1. From risk-based to resilience and sustainability-based decision support

The pursuit to create optimal well-being conditions for society through achieving an acceptable balance between safety and growth in the domains of social-ecological-engineered systems has gradually evolved from risk-based to risk-informed to sustainability and resilience-based approaches to the governance and management of risks. While there are clear differences between these approaches, the terms are often used inconsistently in the literature. In what follows, the differences between these approaches are briefly outlined. Subsequently, the concept of resilience is discussed in detail from the perspective of the different disciplinary fields. Finally, analyzing the commonalities among the different perspectives, it is assessed whether a synthesis of risk, sustainability and resilience in a common framework and metrics is possible and desirable and whether there is evidence of such a framework operationalized in practical application in either the public or private sectors.

At a very basic level, the difference among those approaches is one of scope. The risk-based approach encompasses the technical part of a risk assessment, which typically includes a system and scope definition for a particular problem, a hazard identification, a probabilistic analysis of the realization of the hazard(s), and a consequence analysis (usually constrained only to direct consequences). The risk-based approach helps to identify the risks associated with a given activity and prioritizes efforts to minimize or eliminate them. It is based primarily on a narrow set of model-based risk metrics, which are often highly idealized, i.e., rest on significant assumptions with regard to the target system in the 'real' world the model is supposed to represent. Considerations of indirect consequences (economic, social or environmental) and stakeholder concerns are generally not part of risk-based decision-making. Sometimes risk-based and evidence-based decision support is used interchangeably in policy publications (grey literature) to emphasize a purported 'scientific objectivity' in the risk governance process. The risk governance structure in this case is a top-down structure based on the reliance of public authorities (or business executives) on subject matter experts to procure legitimacy for their decisions. The output of risk-based analyses is typically expressed in quantitative terms, which allegedly adds to the perception of objectivity of scientific evidence.

In contrast, the risk-informed approach is more holistic in that it incorporates the modeling of preferences of the relevant stakeholders, ranking and prioritizing decision alternatives, and defining risk acceptance criteria. It considers both direct and indirect consequences; and accounts for the influence of risk communication and risk perception as powerful drivers of system changes. The risk-informed approach thus goes a step further in drawing a more comprehensive profile of risk by taking in account human judgment into the decision-making process despite its intrinsically subjective quality and precisely because it recognizes that decision-making is a value-driven activity.

Methodologically, risk and sustainability are assessed through different methodologies, the first taking basis in predictive methods and aiming to produce knowledge about the dynamics of a system's constituents or between systems; the latter, in predominantly deterministic methods that result in system representations. To the best of our knowledge, the only framework to date that combines risk assessment with sustainability assessment is proposed by Faber (2018).

Increased interest in the concept of resilience over the past decade can be seen in the light of and as a consequence of trends and shifts in the strategic orientation of risk governance and management. One of the most prominent trends in this respect is the shifting perception of risk as a threat that should be eliminated or controlled through top-down management strategies enforced by policy makers, executives and experts to a perception of risk as a given uncertainty that is better managed through proactive mitigation, capacity building and participatory efforts that are put in place prior to a disruptive event, i.e., during the preparedness stage.

Preference for investing in preparedness over reconstruction is just one driver that has prompted interest in the concept of resilience; another one is the notion of 'inclusivity' in its ubiquitous applications in governance, economics, and ethics. Interest in inclusivity could already be witnessed in the shift from risk-based to risk-informed governance of risks in that for the latter, capacity building is contingent upon the inclusion of a spectrum of societal stakeholders whereby issues like social cohesion, trust, social capital, legitimacy and transparency of decisions, and not least distributive justice are integrated into the overall risk governance framework. Finally, building on the temporal dimension introduced in the sustainability perspective, the resilience perspective goes even further in considering the lifecycle of products and processes as it aims to assure a successful transformation of the system as a qualitative improvement of the

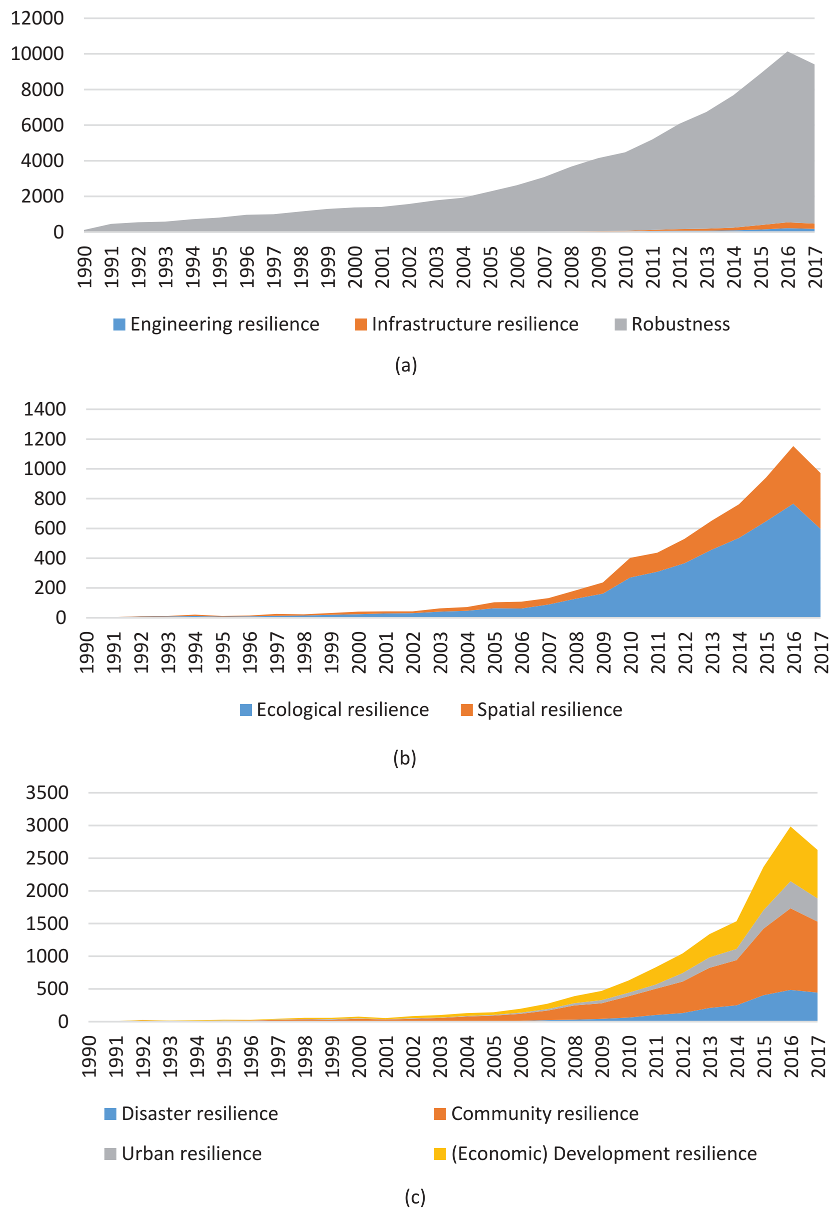

Figure 20. (a) Resilience from the perspective of engineered systems. (b) Resilience from the perspective of ecological systems. (c) Resilience from the perspective of social systems.

system's design and functionality manifested in notions such as *value added, increasing asset value, extending life-cycle, multiple functionalities*, etc.

In the following, the concept of resilience and how it is understood and used in different disciplines is outlined. There is no commonly agreed definition of the term. It is defined differently in each application area from ecology to engineering to mathematics and graph theory, to the health sciences, to psychology to disaster and emergency management to economics to international development. That different types of complex biological and non-biological systems exhibit similar structures, properties and behavior have been exemplified in numerous studies (Barabási, 2009; Gunderson & Holling, 2002; Holling, 2001; Lansing, 2003; Schneider & Kay, 1994; Sundstrom et al., 2014; Watts & Strogatz, 1998). What unifies all the different interpretations of resilience is that resilience theories can be seen as comparative theories of systems and their dynamics, particularly complex adaptive systems (CASs) such as ecosystems, social systems, economies, and infrastructures, or any combination thereof. It is precisely through this general systems perspective that the combination of risk, sustainability and resilience can be approached.

In the present paper, three groups of perspectives on resilience are considered corresponding to ecological, engineered and social systems perspectives. For each, a definition and key authors are provided, together with brief explanations of the main concepts, followed by an examination of the methods and metrics applied or proposed to operationalize resilience, i.e., move from a strategic understanding of the concept and normative goals and requirements settings to operational scientific frameworks for resilience assessment.

Figures 20(a–c) illustrate the composition of the three dominant resilience perspectives. In Figure 20(a) it can be seen that resilience from the perspective of engineered systems is heavily dominated by research on Robustness. In fact, Robustness has by far and large the largest volume of research and the longest history. The adoption of the term *resilience* from the other domains is a very recent phenomenon (mostly in the past decade). Even Ecological resilience, which is often quoted in the literature as the founding discipline of resilience, is a late comer in adopting the term. In the context of ecology, the term *resilience* came to replace an older term – *persistence*. This cannot be seen in the timeline, but it is easily identifiable in the cluster maps and accompanying meta-information tables in the data report.

In Figure 20(b) the evolution of the ecological perspective, with its two complementary sub-fields Ecological and Spatial resilience is shown.

Finally, in Figure 20(c) resilience from the perspective of social systems is depicted through the conceptually related disaster, community, development and urban resilience.

4.2. Resilience from the ecological systems perspective

4.2.1. Ecological resilience

The concept of resilience originated in the field of ecology, from where it spread to the academic community at large and to practical domains of engineering, organizational management, development and the humanitarian aid field. Holling (1973) defines resilience as the amount of disturbance a system can withstand before shifting into an alternative stability domain. In Walker et al. (2004) resilience is defined as 'the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks.' Walker and Salt (2006) use the above definition of resilience to discuss non-linear dynamics of complex adaptive systems such as social ecological systems (SESs), arguing that the dynamics between periods of abrupt and gradual change and the capacity to adapt and transform so as to persevere are what defines the resilience of SESs.

Sharp shifts in the behavior of systems, also termed *regime shifts*, are one of the key concepts in ecological resilience and are fundamental to the subsequent development of the concept of planetary boundaries. The non-linear cause and effect dynamics are discussed in depth in the mathematical literature on dynamical systems (Kuznetzov and Levitin, 1997; Scheffer, 2009). Scheffer (2009) elaborates on the limitations of the dynamical systems theory to account for changes in the nature and properties of the systems themselves over time. Folke et al. (2016) argue that understanding of the qualitative changes of systems can be gained by studying linkages between ecosystems and social systems, and that it is the feedback loops between them that make them interdependent and determine their overall dynamics. Adaptability and transformability are seen in this context as the main capabilities that make a system resilient. Adaptability refers to the capacity of SESs to learn, synthesize knowledge and experience, adjust behavior to both internal and external forces and processes while maintaining stability, or *basin of attraction* (Berkes et al., 2003; Folke et al., 2016). Transformability, on the other hand, is defined in Walker et al. (2004) as 'the capacity to create a fundamentally new system when ecological, economic, or social structures make the existing system untenable.' Although most of the literature on ecological resilience is deliberately non-normative, concepts such as adaptability and transformability are loaded with normative socio-political content, especially with regard to the social transformation of variables such as identity, values, established relations among actors, institutional power arrangements, shifts in perceptions and re-framing of worldviews and perspectives, and deliberately forced transformational changes set in motion by particular governance objectives and policies. Thus, the claim for non-normativity that the ecological resilience school strongly emphasizes is empirically non-tenable. This is especially the case where building systems resilience is a normative objective of sustainability, itself a loaded normative concept.

The ecological school makes a distinction between *specified* and *general resilience*. Specified resilience addresses the question 'Resilience of what, to what?' (Carpenter et al., 2001), which is analogous to posing a question about the boundaries of risk: risk of what, by whom, to whom? Put in this manner, resilience (and risk) refer only to a part of the system and some particular control variable related to one or more identified disturbances (or hazards). Cifdaloz et al. (2010) drawing on Highly Optimized Tolerance theory developed by Carson and Doyle (2000) discuss how increasing resilience of a system's component to specific shocks may result in loss of resilience in other components or undermine the resilience of the system as a whole.

General resilience refers to any and all parts of a system. It does not focus on specific disturbances;

rather, it is associated with the capacity to respond to any uncertainty. Specified resilience is easier to operationalize as quantitative metrics and indicators can be developed with respect to specific disturbances. It is this view of resilience, which is typically adopted in the engineering domain. General resilience has resisted operationalization, and to-date is largely used to describe normative goals and requirements.

From the distinction between specific and general resilience, it is clear how another distinction has emerged between resilience seen as an *outcome* and resilience as a *process*. As an outcome to a goal or a set of priorities, resilience can be characterized as a measure of performance, retrospectively, from some defined stability state of the system in the past through the disturbance event and the time it takes to recover functionality to the level existent prior to the shock. This perspective is linked to *engineering resilience* and *community resilience* in the context of disaster and emergency management. From the process-related perspective, resilience comes closer to the general resilience in ecology. A number of studies have proposed that process-related resilience can be measured in actions rather than system properties (Hollnagel et al., 2011; Seager, 2014, 2016). Actions here refer to the system's ability to sense and organize information, anticipate a disturbance, adapt its behavior, learn, and function at all times in response to internal and external stressors.

In addition to the outcome and process views of resilience, another perspective identifies resilience with *resources* that act as system redundancies or internal capabilities (Eisenberg et al., 2014, Linkov et al., 2013a, 2013b). According to Snell et al. (2016), this perspective is largely undertaken by the U.S. Department of Homeland Security and applied to the National Infrastructure Protection Plan (NIPP 2013).

Resilience, stripped of particular context is neither good nor bad for human welfare. In the majority of literature on ecological resilience, where resilience is seen as a process, there is a deliberate disassociation from normativity. Gunderson et al. (1995), Gunderson and Holling (2002), Walker and Salt (2006) have emphasized that while humans play a role in changing the biophysical ecosystem conditions, they are not the primary indicators of system change, arguing that a resilience approach is not intended to choose among outcomes but rather to understand which system dynamics might be favored over others. Similarly, Walker et al. (2006) and Folke et al. (2010) have pointed out that operationalizing resilience should aim at increasing natural and social capital, preparing for cascading consequences, adjusting to mismatched cross-scale linkages, and steering the system out of undesirable basins of attraction. Poverty traps are an example of an undesirable basin of attraction (as discussed in the economics literature), which exhibit high level of resilience but are a non-desirable system state. Sundstrom et al. (2014) further point out that the cross-scale resilience model developed in ecology to explain the emergence of resilience from the distribution of ecological functions within and across scales can be applied to non-ecological systems, i.e., anthropological, economic, etc., for the non-normative quantitative assessment of resilience.

When, however, resilience is seen as an outcome, it is strongly associated with sustainability and takes basis in rigorous normative values focused on identifying desirable future alternatives, assigning values to these alternatives through developing sustainability indicators and promoting policy interventions that advocate fundamental transformations of the socio-political system in which decisions are made.

In what follows we discuss the extent to which the ecological resilience perspective is operational and what have been to date the methods and metrics used to measure it.

At the more qualitative, conceptual end of the spectrum, the notion of *panarchy of nested adaptive cycles* provides a heuristic understanding of the interplay of resilience, adaptability and transformability across multiple scales (Allen et al., 2014).

Another method is the development of early warning (EW) indicators, which allows the assessment of when a system approaches a critical threshold and potentially impending regime shift. Dakos et al. (2012) present a summary of currently available EW methods and apply them to two simulated time series typical of systems undergoing critical transition.

Classification and Regression Tree analysis, and their Bayesian implementation have been used to identify scaling structure based on size characteristics in ecological (e.g., animal size) or urban (city size) systems (Sundstrom et al., 2014).

Finally, time series and spatial modeling are additional methodologies used in the domain of ecology. Angeler et al. (2016) for instance identify discrete temporal frequencies at which patterns in complex systems manifest. Allen et al. (2016) have used spatial modeling techniques to reveal discrete geographical extents and variation in relevant variables, showing how such methods have the potential to assess how entire regions at a landscape level, i.e., beyond ecosystems, affect and are affected by local and regional environmental processes and governance.

4.2.2. *Spatial resilience*

Stemming from the ecological resilience knowledge domain, the concept of spatial resilience has the potential to unite many of the other resilience perspectives by looking at various spatial attributes of ecological, social and engineered systems to understand the identity (or boundaries) of a system, its structure (components and their distribution), and its behavior (flows, feedbacks and connections among the components as well as external interactions). The concept was first used by Nystrom and Folke (2001) in studies of coral reef and rain forest disturbance to underline the importance of *ecological memory* in keeping a system's identity during re-organization.

The first comprehensive description can be found in Cumming (2011) who defines spatial resilience through the spatial arrangement of, differences in, and interactions among internal and external elements of a system, arguing that both internal and external elements must be considered in relation to other aspects of system resilience, including the system's structure, interactions, ability to maintain its identity while undergoing change and, finally, a system's inherent learning capacity. The spatial boundaries of a system are not necessarily a layout in space but more in function. Internal elements are thus those that are related and interact with each other and may be defined in social, economic or ecological terms by a geographical boundary at a *landscape level*. The external elements include the context, which is to be understood as the non-focal spatial surroundings, connectivity and spatial dynamics that influence a system's identity from outside the system boundaries.

Quantifying spatial resilience is still in an early stage of development. Allen et al. (2016) provide an extensive literature review of spatial resilience research and propose a procedural roadmap for operationalizing spatial resilience. The roadmap includes explicit consideration of spatial variability in both the system and disturbance under consideration; inclusion of internal and external spatial elements in the definition of the system's spatial boundaries; the identification of thresholds and tipping points; and the determination of ecological memory that influences present and future system states.

4.3. Resilience from the engineering systems perspective

In the context of technical systems, three terms are used, often interchangeably, to talk about resilience: engineering resilience, infrastructure resilience and robustness.

Scientists from the ecological field of resilience have been keen to draw a distinction between their work and that of their peers in the engineering domain. Allen et al. (2016) and Angeler and Allen (2016) point out that the assumption made in engineering resilience with regard to a single equilibrium state in complex systems is not applicable to complex adaptive systems such as SESs. Engineers, on the other hand, have embraced much of the resilience theory stemming from the ecological perspective. Fiksel (2003) argues for an alternative to traditional engineering practices focused on anticipating and resisting disruptions, embracing the idea of developing sustainable systems through 'designing systems with inherent resilience by taking advantage of fundamental properties such as diversity, efficiency, adaptability, and cohesion.'

Hollnagel (2014) defines engineering resilience in basically the same terms as general resilience in ecology, namely as 'the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions.' He then outlines four main characteristics of resilience engineering: (i) the ability to respond to known and unknown disturbances; (ii) the ability to monitor system states; (iii) the ability to learn from the consequences of past events and decisions; and (iv) the ability to anticipate and proactively adapt to change. While Fiksel's and Hollnagel's understanding of engineering resilience is entirely compatible with the ecological perspective, most other sources contrast the two in terms of divergent views on singular or multiple states of equilibrium in complex systems dynamics and the focus of engineering resilience to restore system functionality to a previously defined level of performance.

In structural reliability and risk analysis, the concept of *robustness*, not resilience, is used to characterize the sensitivity of an engineered system's performance to a well-defined set of disturbances, or loading conditions. The Joint Committee on Structural Safety (JCSS), a pre-normative body in the field of civil engineering, defines the robustness of a system as the ratio between direct risks and the total risks (where total risk is the sum of all direct and indirect consequences) for a specified time frame and considering exposure events and all relevant damage states for the constituents of a system (JCSS, 2008) Robustness can be understood then as the degree of resistance relative to a particular set of exposures. When potential regime shifts are not considered and the context of the analysis is a regime's steady state, the concept of robustness is the same as that of specified resilience (Yu et al., 2016)

Janssen and Anderies (2007) examine robustness-fragility trade-offs in SESs – a notion that refers to the observation that designed features meant to increase robustness of particular system component(s) to particular stressors, lead to weakening or 'fragilizing' of other stressors and/or components. It is in this notion that the main incompatibility between (i) specified and general and (ii) ecological and engineering resilience resides. In engineered human-technical systems the robustness-fragility trade-off can be seen as two opposing strategies in the design of systems, namely *'fail-safe'* design based on robustness vs. *'safe-fail'* design based on resilience considerations (Park et al., 2013).

Like ecological resilience, the engineering resilience perspective tends to be more descriptive than normative in the sense that it is concerned with measuring the *elasticity* of a system in absorbing and recovering from disturbances. The product of such descriptive analysis is typically a technical risk assessment. However, once the assessment results are contextualized into a decision problem, where stakeholder preferences are taken into account, the degree of normativity increases both with regard to economic and ethical considerations.

Quantifying resilience of engineered systems has typically been based on: (i) networks modeling; (ii) system performance modeling; (iii) composite indicators development and early warning methods; and (iv) hybrid modeling, comprising two or more of the above methodologies. Some examples of state-of-the-art methodologies and their applications are provided below.

In the case of networks modeling, computational methods and graph theory form the basis. Newman (2006), Barzel and Barabási (2013), Barabási (2016) apply network theory as a basis for system representation, arguing that topological similarities in engineered, natural and social networks (e.g., roads, rivers, communities) show functional self-similarity and scale independence.

In the case of system performance modeling, which is also the more widespread method in applied engineering contexts, quantitative data from historical events, computational infrastructure models and subject matter estimates are used to model the performance of a given system. The resulting performance measures are then applied in planning and decision-making processes as the metrics can be used to estimate and evaluate the costs and benefits of proposed resilience interventions.

Hollnagel (2011) develops the Resilience Analysis Grid (RAG) also called 'RAG profile for an ability', which summarizes the balance between the abilities to monitor, anticipate, respond, and learn. RAG is a process measure providing information about the current situation and can be used to monitor performance at discrete times, defining areas for improvement.

Hollnagel (2012) uses the Functional analysis Method (FRAM) – traditionally applied to model human error in the context of operational safety in the health and transport sectors – to study the dynamics of complex socio-technical systems by modeling the potential variability of each function and possible dependencies among functions.

Indicators and Early Warning methods are more attribute-based and include categories of system properties, which are typically regarded as enhancing resilience, e.g., robustness, adaptability, resourcefulness, etc. Their products are usually qualitative or semi-quantitative estimates of resilience, which can, in turn, be operationalized through procedural processes. Such methods are typically applied in the military, civil defense and the disaster risk management and emergency contexts. Øien et al. (2012) describe what is termed Resilience-based Early Warning Indicators (REWI) method, which has been applied in the evaluation of causes and factors leading to the Deep Water Horizon accident, showing retrospectively that the accident may have been prevented had insight from relevant indicators been taken into account in the management process. Empirically tested in a case study on the successful recovery of high-risk incidents (Størseth et al., 2009), the REWI method incorporates some fundamental attributes of resilience, termed contributing success factors (CSFs): risk understanding, anticipation, attention, response, robustness, resourcefulness/rapidity, decision support, and redundancy. For each CSF, measurable indicators are then developed.

In the context of facilitating resilience assessment of critical infrastructures, Linkov et al. (2014) propose a similar indicator-based methodology, starting with a functionality curve of the critical infrastructure system and adding resilience dimensions as sequential time phases: understand risks, anticipate, prepare/adapt, be aware/attentive, absorb, respond, recover, and adapt. While both methodologies explicitly link risk and resilience assessment, the REWI method's outputs are early warnings, whereas Linkov's application is intended to provide a measure of resilience for each dimension or temporal phase along the functionality curve.

Woods et al. (2013) propose the Q4-Balance framework (Balancing Economy-Safety Trade-Offs), utilizing a balanced portfolio of indicators, grouped into four classes: economy-reactive, economy-proactive, safety-reactive, and safety-proactive.

Furthermore, a number of hybrid methods have been proposed and applied. Vugrin et al. (2011) apply the Infrastructure Resilience Analysis Methodology (IRAM), which combines performance-based metrics and resilience attributes whereby the consequences of a specified disruption in an infrastructure system can be modeled deterministically and/or probabilistically while three resilience attributes (absorptive capacity, adaptive capacity and restorative capacity) can be used to identify resilience limiting properties, thus providing input at the system design level. An additional component of IRAM is a six-step process that guides the user through the application. This process has been applied in the contexts of transportation, chemical manufacturing, public health and energy (Vugrin et al., 2011, 2014, 2014, 2015).

A logic model is proposed by Willis and Loa (2015) of the Rand Corporation as a way of aligning resilience metrics with strategic and operational decision-making. Based on a hierarchy of metrics that connects inputs to outputs, the model can help explain from an operational perspective how resources (budgets, equipment, spare parts, people) contribute to desired strategic outcomes (reduced costs/damage, improved welfare, increased economic activity.

Moore et al. (2016) attempt to quantify resilience of SESs using network theory by focusing on two state variables: *system performance* (e.g., functions such as ecological, social or infrastructure-related) and *adaptive capacity*.

Ganin et al. (2016) propose to measure resilience as critical functionality based on performance recovery from a single shock by using multi-level directed acyclic graphs and interdependent coupled networks.

Klammler et al. (2016) develop a model of interdependence for urban technological systems (infrastructure) and socio-economic systems (institutions), using multiple metrics of coupled systems performance under a stochastic disturbance regime.

Finally, two methodological frameworks should be mentioned which combine risk, sustainability and resilience assessment under one umbrella. Anderies et al. (2013) argue for a synergetic approach to resilience, robustness and sustainability as a means of developing a global change policy that addresses the multi-scale and multi-level challenges associated with global change. Sustainability is referred to as the analytical framework that structures the decision-making process at multiple scales and comprises multiple actors that together can identify, rank and select development pathways that meet performance criteria: 'When sustainability is conceptualized in this way, the importance and respective roles of the full range of academic disciplines, including the humanities, social and natural sciences, decision science, and engineering become clear.' Robustness and resilience ideas can be used within the overarching sustainability framework to help inform decision support across scales (specified vs. general resilience) and systems boundaries as well as levels of organization.

An operational integrated model of risk, resilience and sustainability is developed by Faber (2018), where an underlying decision analysis framework facilitates the decision optimization of alternative pathways for sustainable development. The framework provides a rationale for how resilience, efficiency and sustainability relate to each other. Methodologically, it demonstrates how failure events for inter-linked social-ecological-industrial systems propagate through failure of the global environmental system, failure of the social system and failure of the infrastructure system. The framework takes basis in Bayesian decision analysis, life cycle assessment (LCA), the concept of planetary boundaries, and the concept of the Life Quality Index (LQI), used to model impacts to welfare and social capacity.

4.4. Resilience from the social systems perspective

The context of the social systems perspective of resilience is rather broad and encompasses recovery processes in the aftermath of disaster events for social-ecological and technical systems. Four terms may be used in this context: disaster resilience, community resilience, urban resilience and (economic) development resilience. The terms disaster and (economic) development resilience are typically used in reference to developing countries only. Community resilience and urban resilience are used in reference to both developing and developed countries.

In the area of disaster risk management (DRM), the concept of resilience is approached from two distinct perspectives, which follow the traditional division in the DRM field between the natural and applied engineering sciences on one hand, and the social sciences, on the other hand. The former focuses primarily on the temporal aspects of resilience before the occurrence of a hazardous event, with an emphasis on mitigation measures aimed at reducing the frequency and magnitude of hazards and strengthening property to prevent damage (Bruneau et al., 2003). Here resilience is understood as a function of (i) reduced failure probabilities, (ii) reduced consequences (e.g., fatalities, structural damages and socio-economic consequences), and (iii) reduced time to recovery (e.g., restoration of system functionalities to a pre-defined 'normal' level of performance. This view of resilience is essentially the same as that of engineering resilience and as such depends on properties such as robustness (the capacity to withstand stress without loss of functionality), redundancy (the extent to which system components are substitutable), resourcefulness (the ability to make sense of a crisis situation and apply resources accordingly), and rapidity (the ability to restore the system to 'normal' functionality in a timely manner (Bruneau et al., 2003; Liao, 2012).

In the DRM literature on resilience, the term 'community resilience' is typically used rather than engineering resilience, especially in the context of disaster management, which largely falls in the social sciences domain. Regardless of which term is used, there are many overlaps between engineering and community resilience. In an attempt to develop a quantitative framework for the seismic resilience of communities, Bruneau et al. (2003) identify four dimensions of community resilience: technical, organizational, social, and economic. They link these dimensions to key community infrastructural elements: power, water, hospital, and local emergency management system. Such coupling allows them to identify and quantify system performance criteria measures for resilience.

In the context of flood risk management, the concept of engineering resilience has been applied by Garvin (2012) but supplemented by the broader social-ecological resilience from the ecological perspective (Dawson et al., 2011; Huntjens et al., 2011; Sayers et al., 2002; Zevenbergen et al., 2013) with the aim to counter-balance the focus on protection through large-scale structural engineering measures such as flood embankments, channelization, etc., with organizational and land use prevention and preparedness measures. Quantitative flood resilience models are based on indicators, which relate system response to flood waves (Mens et al., 2011). However, despite broadening indicators to include reaction threshold, amplitude, graduality, and recovery rate (Gersonius, 2008), a measure of the overall resilience of a system remains elusive as the indicators cannot yet be aggregated and expressed in one numerical value (Zevenbergen, 2007).

A second stream of research on disaster resilience stemming from the social sciences focuses explicitly on the situation after a disaster has occurred and is particularly concerned with the reduction in the flow of goods and services, often referred to in the literature as *business interruption* (Tierney, 1997). Economic resilience and international development resilience could also be included in the DRM context of resilience.

The most recent definition of resilience in the DRM context can be found in the Hyogo Framework for Action 2015–2030. Their resilience is "the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner including through the preservation and restoration of its essential basic structure and functions (UNISDR, 2015a). This definition is practically the same as that of engineering resilience; however, the operational context is somewhat different. There is significantly higher normativity in DRM – a landscape dominated by high-level public sector stakeholders at the national and international organizational level. Their normativity, coupled with a strong impetus for measuring outcomes of policy directives is by necessity biased toward searching for linear cause-effects and predictability as preferences for action.

Stemming from the research domain of ecology and building on the concept of *planetary boundaries*, Homer-Dixon et al. (2015) develop an integrated framework to represent the causal patterns, intermediate processes and ultimate outcomes of what they call *'synchronous failure'* – a new type of global crisis resulting from multiple, simultaneous and interacting global stresses, such as population growth, climate change, resource scarcity and financial instability. Synchronous failure results from the combination of (i) unsustainable economic activity induced by demographic pressure; (ii) increased connectivity and speed in the channels transporting material, energy and information among the components of human technological, economic and social systems (Helbing, 2013) and (iii) homogeneity in human social systems, institutions and cultures whereby efficiencies achieved through economies of scale reduce redundancies that are essential for systems resilience. For Homer-Dixon et al. (2015) the global energy system has a synchronizing role in the evolving behavior of other systems such as water, food, climate, etc. It is therefore argued that interventions that enhance societal resilience and reduce the risks of synchronous failure must incorporate the concept of planetary boundaries for disaster preparedness at the global level.

While much of the literature on resilience in the DRM context is related to framework formulations aimed at (i) identifying goals and requirements for what hypothetically constitutes a resilient society or (ii) providing a system representation of the causal interactions between systems components, some methods have been proposed to measure resilience so that the concept can be utilized not only for strategic normative goal setting but be operationalized through pragmatic application. There is a strong consensus in both the scientific and policy communities on sustainability and resilience goals; however, when it comes to what to measure and to how to measure it, disagreement is widespread and organized quite distinctly around separate disciplinary fields.

Economists working in the domain of international development and humanitarian resilience emphasize the integration of the knowledge on poverty traps into the measurement of resilience. This is because countries with high poverty rates, food insecurities, inadequate infrastructure, and shattered social institutions are particularly exposed to systemic disturbances that contribute to tipping over threshold boundaries and generating failures that cascade through social-ecological systems (Barrett & Carter, 2013). Moreover, resilience as a systems characteristic is stripped of its neutrality that a descriptive scientific perspective, purely interested in systems dynamics provides it. From a socio-economic perspective, resilience is a desired outcome of the current non-poor whose aim is the maintenance of the present stable state. For the current poor, the objective is the opposite, i.e., to disrupt the present balance, seeking transformational change.

Building on Sen's concept of capability (1999), Barrett and Constas (2013) propose a person's well-being, or a scaled up aggregate, e.g., household, village, nation's, as the key variable in measuring resilience, and express resilience as a function of well-being and resource availability for current and future temporal dimensions. They combine probability estimates of poverty in each sequence of time periods with normative assessment of an appropriate tolerance level for the likelihood of being poor over time as a heuristic to classify individuals, communities, etc., as resilient or not.

Rose (2016) argues that economic resilience can be measured through established economic models related to the behavior of producers, consumers, government agencies, markets, and entire economies through a combination of effectiveness and cost measures. He distinguishes between *static economic resilience* (the efficient use of remaining resources at a given point in time) and *dynamic economic resilience* (the efficient use of resources over time for investment in repair and reconstruction). He then proposes that static resilience can be measured as an expression of the amount of business interruption (BI) prevented by the implementation of some resilience intervention measure (or set of measures). Dynamic resilience can be expressed as the reduction in recovery time in addition to the reduction of BI. The baseline for measurement can be taken to be the maximum potential BI loss in the absence of an intervention (Rose, 2016).

Cutter et al. (2013) develop a qualitative classification scheme that uses sets of indicators according to which a community can be classified as resilient or not. The sets are composed of aggregates such as community competence, infrastructure, and institutional, economic, social, and ecological indicators. Each indicator is comprised of about 10 variables and their respective positive or negative effect on resilience.

A similar classification tool is the Disaster Resilience Scorecard for Cities developed by the UNISDR and the IBM Corporation (UNISDR, 2015b). The scorecard is intended for urban planning whereby cities can evaluate their preparedness or current level of disaster resilience, identify priorities for action and investment, and track their preparedness over time. The scorecard facilitates the evaluation of institutional collaboration, risk assessment, building codes, natural buffers, and warning systems.

4.5. Trade-offs between risk, sustainability and resilience

In this section, we examine how emergent concepts in the context of integrating risk, sustainability and resilience considerations have been framed to highlight trade-offs between growth, efficiency and the preservation of a safe operating space for humanity with respect to ensuring the functionality of the Earth system. Our discussion focuses on the Group 3 concepts identified in the bibliometric analysis: (i) Planetary Boundaries, (ii) Natural Capital and Ecoservices, (iii) Circular Economy, (iv) Social/Urban Metabolism, (v) Inclusive Economy/Wealth/Growth, (vi) Degrowth, (vii) Adaptive Governance, (viii) Social Cohesion, and (ix) Social Ecological Systems. Cluster term maps are provided for selected concepts. The interested reader can find term maps and all accompanying metadata in the bibliometric report.

4.5.1. The concept of planetary boundaries

In risk analysis and quantitative sustainability assessment based on life cycle assessment (LCA) methodology, defining the system boundaries is the initial step in the process. In the context of risk analysis, a system definition is the spatial, temporal and relational representation of all relevant hazards (also termed exposures), the assets (e.g., buildings, structures, components, lifelines, technical equipment, procedural processes, humans and the environment), direct consequences (consequences related to damages on the individual constituents of the system, also termed marginal losses), and indirect consequences (consequences related to the loss of the functionalities of the system). According to Faber (2009), the chosen level of detail must be such that it can facilitate a logical representation of events and scenarios of events related to the constituents of the system, which individually or in combination may lead to adverse consequences. The purpose of identifying the spatial, temporal and functional boundaries of a system is to set the scope for the decision problem, facilitate the consistent ranking of decision alternatives as well as allow updating of the knowledge about the individual constituents that may become available in the future.

Similarly, goal and scope definition is the first phase in LCA methodology, which is applied in the context of quantitative sustainability assessment. The goal and scope definition includes the reasons for carrying out the study and the intended application and audience. It is also the place where the system boundaries of the study are described and the functional unit is defined. According to ILCD, 2010, three decision context situations of practical relevance in LCA can be differentiated, termed, respectively, ‘Situation A: Micro-level decision support’, “Situation B: ‘Meso/macro-level decision support’, and ‘Situation C: Accounting’. While the first two deal with scaling effects of the system boundaries, the latter relates to consequences that have resulted in the past or may result in the future based on decisions already taken, hence it is not scale specific.

It is clear from the practice of risk and sustainability analyses that the process of defining the boundaries of a system under consideration is directly related to decision-making and risk governance. But while risk governing structures and institutional and institutionalized processes are more or less clearly defined at the micro- and meso-scales, there is no such governance structure at the global-scale, i.e., that of the planet. In this context, the concept of planetary boundaries, first outlined by Rockström et al. (2009) and updated in Steffen et al. (2015), accounts for the capacity of the Earth system and its biosphere to sustain adequate living conditions for humanity. Stemming from a long tradition in ecology science research on dynamics in social-ecological complex systems, thresholds and regime changes, the concept of planetary boundaries was proposed in light of accumulating evidence that exponential growth of human activities is putting such stresses on the Earth system that could destabilize critical biophysical systems and lead to abrupt and irreversible environmental changes at continental to global scales, possibly pushing the planet out of the Holocene state – the only known state of life-sustaining conditions for humanity.

In the original formulation, the planetary boundaries concept is advocated as a framework for estimating a safe operating space for humanity with respect to the functioning of the Earth system (Rockström et al., 2009). The authors identify key Earth system processes and attempt to quantify for each process the boundary level that should not be exceeded if unacceptable global environmental change is to be avoided. Unacceptable change is defined in relation to the risk and uncertainty humanity faces in the transition of the planet from the Holocene to the Anthropocene. Drawing on research from the discipline of ecology (Carpenter et al., 2001; Folke et al., 2004; Hughes et al., 2007; Scheffer, 2009), they present evidence from local to regional scale ecosystems that incremental changes in key control variables such as biodiversity, harvesting, soil quality, freshwater flows, and nutrient cycles, can trigger abrupt system change states once a certain threshold is exceeded. Nine planetary boundaries are identified: climate change, stratospheric ozone depletion, atmospheric aerosol loading, ocean acidification, biochemical flows, freshwater use, land-system change, biosphere integrity (functional and generic diversity), and novel entities. In the updated concept outline, Steffen et al. (2015) elaborate on the scientific underpinnings of the PB framework and present the status of the control variables for seven of the planetary boundaries. The authors further claim that climate change and biosphere integrity are the ‘core’ planetary boundaries based on their fundamental importance to the Earth system.

The concept of planetary boundaries builds on and extends approaches based on various sources. One such inspiration is the *limits-to growth* notion outlined in the book of the same title, where the problem of exponential economic and population growth is modelled in the context of finite resources (Meadows et al., 1972, 2004). Another one is the concept of *safe minimum standards*, originally proposed by the German natural resource economist Ciriacy-Wantrup as a way to eliminate catastrophic risk outcomes in the context of conservation and the management of natural resources, and applied in cases where probabilistic consequences assessment and cost-benefit analysis are unreliable (Bishop, 1978; Ciriacy-Wantrup, 1952; Crowards, 1998). A third relevant concept is the *Precautionary principle* in the formulation of Raffensperger and Tickner (1999) in their handbook guide for the science and environmental health network, where they state: ‘When an activity raises threats of harm to human health or the environment, precautionary measures should be taken even if some cause-and-effect relationships are not fully established scientifically.’ Finally, the *tolerable windows* approach (Petschel-Held et al., 1999; WBGU 1995) a scheme for integrated assessment of climate change, adds to the theoretical basis of the planet boundaries.

In its scientific basis, the concept of planetary boundaries merges several scientific domains, which could be grouped around the following areas: (i) ecological economics, (ii) geoscience and sustainability science, and (iii) resilience and complex systems dynamics. In the following, some examples are given of the state-of-the-art research in PB as it relates to the aforementioned three areas of scientific inquiry.

Crépin and Folke (2014) relate current knowledge on biosphere dynamics and the PB framework to the economics literature on safe minimum standards, precautionary approaches, economic growth, regime shifts and thresholds. They argue that PBs can be interpreted as risk thresholds, which would help create consensus around them. While societal preferences of risk acceptance may be driven by risk aversion, they claim that preferences should have no impact on the location of the boundaries themselves. They further propose that the concept of resilience can be applied in the context of risk management whereby resilience could be conceptualized as an insurance in relation to growth within PBs.

van den Bergh and Kallis (2012) compare two alternatives to the growth paradigm in institutional economics, namely *a-growth* and *de-growth* in the context of the sustainability of economic growth given the concept of PBs. The a-growth approach proposes to ignore GDP as an effective indicator of social welfare as it (i) estimates the costs, not the benefits of market-related activities, excluding informal or non-market activities and (ii) fails to capture unpriced effects of growth related to the use of natural resources and ecoservices. Unconditional GDP growth is thus seen as incompatible with progress in areas such as climate, labor, health and public utilities. The a-growth paradigm supports developing environmental, social and economic policies irrespective of their effect on economic growth. The de-growth approach goes further than merely proposing a substitute for the GDP. In Kallis (2011) and Schneider et al. (2010), de-growth is defined as the equitable downscaling of economic production and consumption to ensure that society's resource use and waste stay within safe biophysical boundaries.

While the concept of PBs has been criticized because of a presumed conflict between global equity and environmental sustainability goals, Steffen and Smith (2013) have argued to the contrary that coupling social equity considerations regarding access to resources and ecosystem services with the biophysically oriented PBs builds a synergetic, powerful basis for working toward global sustainability. Building on empirical research that links income inequality to social outcomes at the national level (Wilkinson & Pickett, 2009) they show how greater income equality is not only beneficial to society as a whole, but is of particular benefit to those who are well off in that the wealthy in less equal nations have poorer social outcomes than the wealthy in more equal nations. They speculate that this phenomenon, which has been observed at the sub-national and national levels, could actually be an emergent system property at the global level, implying that it would be in the social interest of wealthy developed nations to reduce the income inequality between themselves and developing countries for both biophysical and social reasons.

Ryberg et al. (2016) examine challenges related to the development and operationalization of a PB-based Life Cycle Impact Assessment (LCIA) method. The challenges are related to technical issues such as modeling and including the Earth system processes and their control variables as impact categories in LCIA and to theoretical considerations with respect to the interpretation and use of LCIA results in accordance with the PB framework.

Fang et al. (2015) discuss the complementary linkages between environmental footprints and PBs. Environmental footprints (water, chemical, carbon, phosphorous, nitrogen, biodiversity, material, etc.) can be regarded as indicators of human demand for ecoservices or environmental pressure in relation to resource extraction and waste emissions. The PB concept provides a set of expert consensus-based estimates of the regenerative and absorptive capacity of the Earth's life-supporting systems. Despite conceptual differences, calculation methods and policy relevance, the authors see significant benefit in the synergy of metrics, which would make possible the benchmarking of contemporary footprints against maximum sustainable footprints thereby indicating the extent to which thresholds have been crossed.

Baum and Handoh (2014) compare PBs and global catastrophic risk (GCR) paradigms and propose a unified PBs-GCR conceptual framework – Boundary Risk for Humanity and Nature (BRIHN) – that integrates the systems resilience perspective of PBs with the probabilistic risk perspective of GCR. Uncertainty here is seen through two different mutually compatible system attributes: the resilience of the system to particular forcings (PBs) and the tendency of the system to result in collapse (GCR). The proposed framework could be applied in analyzing the risk and resilience of any two interacting systems. However, it comes short in its ability to account for interactions between different threats and multiple systems.

Faber (2018) proposes a methodological framework for a joint assessment of risk, sustainability and resilience, where the concept of PBs is applied in the context of a limited budget decision analysis problem. He considers the PBs as a representation of constraints on sustainable societal development at global scale, where the allowable impacts of human activities, over time and space, are limited, and sees the role of governance comprising two essential tasks: the assessment of the total allowable impacts and their allocation. To this end, a decision analysis framework and metrics are developed for optimizing welfare and quantifying sustainability and resilience.

4.5.2. The concepts of natural capital and ecoservices

At a most fundamental level, the trend that shapes the impetus to re-define core concepts such as wealth, growth and utility lies in the shift from studying social systems and institutions on one hand and natural systems and biophysical process on the other hand as separate domains of inquiry. The social ecological systems approach that emerged from the synthesis of ecology and economics emphasizes the embeddedness of social systems and institutions into the all-encompassing envelope of the biosphere, arguing that human well-being in all its dimensions (e.g., material needs, security, freedom, choice, justice, health, and intellectual growth and fulfillment) rests on the capacity of the biosphere to support these. Its main tenet is that social and ecological systems influence each other in reciprocal ways and co-evolve because of mutually reinforcing feedbacks (Folke et al., 2011).

The concept of natural capital emerged in the 1980s from the field of ecological economics as a first attempt to broaden the notion of capital, which in traditional economics refers exclusively to money, tools and machinery used in the production of goods and services, to now also include energy, nonrenewable resources, ecosystem services, and the life-supporting biophysical ecosystems that generate these (Costanza & Daly, 1992; Ekins et al., 2003; Jansson et al., 1994; Kareiva et al., 2011). The traditional model of production of an economy based on the three input factors land, labor and capital, is revised in Folke et al. (2016) so that these factors correspond to natural capital, human/social/cultural capital and human-made capital. The trio human/social/cultural capital is an extension of the traditional labor and human capital and is to be understood as those human institutions involved in the value setting and governance of human actions (Baland & Platteau, 1996; Berkes & Folke, 1992; Dasgupta & Serageldin, 1999; Folke et al., 2016; Pretty & Ward, 2001; Putnam, 2002). Human-made capital is an extension of the traditional notion of capital and includes, e.g., technology and capital markets (Costanza & Daly, 1992; Folke et al., 2016). Human-made capital is also referred to as manufactured capital by some authors (e.g., Dasgupta 2014).

Similarly, while early formulations of sustainability (WCED 1987) viewed the environment, society and the economy as three distinct 'pillars of sustainability,' ecological economists have proposed a re-defined conceptual framework of sustainability, where human well-being is defined and influenced by the inter-relations of the following factors: physical, social, environmental, economic, and psychological (Folke et al., 2016). This coupling of fundamentally social issues (e.g., democracy, health, equality, justice, security) with environmental issues concerning the life-supporting system of the biosphere (e.g., natural resources, ecosystem services, biodiversity) advocates a multi- and trans-disciplinary scholarship and approach to governance and decision-making that is integrative of the natural sciences, the social sciences and the humanities and is polycentric, participatory and inclusive. Renn (2016) refers to this approach as 'inclusive resilience', which he sees as the emerging approach to risk governance. The social-ecological approach is furthermore cross-scale in that landscapes and seascapes are transformed through processes in which local events can produce global consequences while global dynamics are responsible for shaping particular local conditions. How the interaction between scales produces trade-offs that need to be managed through a sustainable, fair and scientifically consistent manner is targeted by both competing and complimentary platforms and frameworks stemming from ecological economics, sustainability science, applied engineering sciences and social sciences and can be approached through a re-evaluation of the notion of growth, which is central to the study of both social and natural systems.

4.5.3. Re-evaluating the concepts of wealth and growth

The authors who originally formulated the concept of PBs take particular care to emphasize the scientific basis of their work as strictly comprising the identification and description of biophysical processes and alterations in the Earth system's functionalities because of human activities. Folke et al. (2009) recognize that human choices and actions will to a large extent determine whether critical thresholds are exceeded, but they distance themselves from any normative proposition by stating that 'the identified thresholds in key Earth System processes exist irrespective of people's preferences, values or compromises based on political and socio-economic feasibility such as expectations of technological breakthroughs and fluctuations in economic growth.' Similarly, the updated conceptual paper of 2015 concludes: 'The PB framework does not dictate how societies should develop. These are political decisions that must include considerations of human dimensions, including equity, not incorporated in the PB framework.' (Steffen et al., 2015)

Normative questions related to population and economic growth, the Earth's carrying capacity, the economic value of natural capital and ecoservices, the circular economy, and inclusive wealth all relate directly to the concept of PBs but are largely studied under the umbrella of ecological economics, applied ethics and branches of engineering and social sciences. While in the 1970s, when ecological economics emerged as an amalgam of ecosystem ecologists and environmental economists, many of the concepts and values they promoted were the fringe of both scientific and political discourse, it is clear that in the past 10–15 years, most of these formulations have infiltrated the full spectrum of scientific disciplines from the humanities to the social, natural and applied sciences and become the norm in policy and scientific circles. Where once mainstream economics promoted value-free analysis through methods such as cost-benefit analysis in the attempt to make economics a ‘hard science,’ the alternative understanding of concepts such as wealth, capital and growth that emerged from ecological economics, is now re-defining society’s understanding, perceptions and expectations at large with regard to the very notions of well-being, happiness, wealth, social and ecoservices, the equitable distribution of all of the above, and the legitimacy of the institutional arrangements responsible for distributing commonly shared resources at local, landscape and global scales.

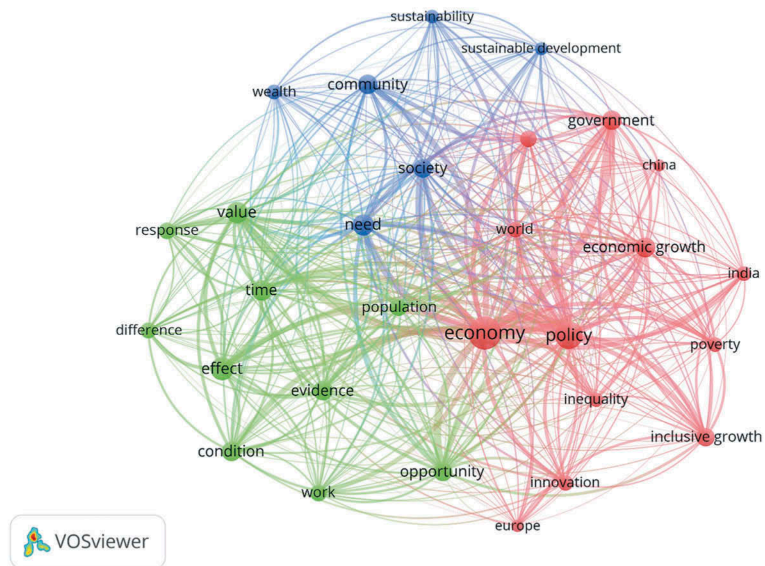

Figure 21. Network map of research on the concept of inclusive economy/wealth/growth.

In what follows, some essential concepts and strategies from the ecological economics domain are briefly outlined as well as how these are applied in theory and in practice to re-define concepts and strategies in the domain of risk and decision-making.

The concept of growth is central to discussion of trade-offs in the context of risk, sustainability and resilience. While economic growth might help produce resources and technologies that could mitigate natural and man-made hazards, help minimize negative consequences of adverse events, and speed up recovery processes in the aftermath of disasters and industrial accidents, economic growth is for the most part achieved at the expense of the planet’s natural capital in the form of extraction activities and pollution.

At a very fundamental level, growth is imagined and experienced as a positive attribute, which is a priori desirable. Belonging to the domain of all things living, growth implies vitality. Conceptually, growth can be framed as a natural phenomenon, a dynamic property that can increase or decrease. Generally, the increase and decrease is imagined as a vertical movement, where more points upwards and carries various positive connotations such as wealth, health, self-realization, fulfillment of potential, etc. Moving down this scale, the decrease in growth spells stagnation, decline, underdevelopment, and halt. Growth can be framed through the metaphor of a living organism going through different life processes: birth, development, maturity, death; or through a mechanistic process metaphor (White, 2003), where growth occurs alongside words such as *trigger, kick start, spark, fuel, drive, accelerate, catalyst, main engine, locomotive, lever, put a damper on, put the brake on, keep on track, pick up steam, derail*. In the latter framing, it is clear that the dynamics of growth are not that of the upward/downward scale of the organic metaphor, which promotes an understanding of growth as a succession of creative and destructive cycles, but rather deviations from a controlled path, whose ultimate purpose is the maintenance of perpetual continuity.

In addition to the organic and mechanistic framings of growth, the notion of limits has been extensively used in the economic literature. Malthus (1798) developed an exponential model of population growth bounded by limited resources. Meadows et al. (1972, p. 1992) examined energy and material limits in a seminal publication ‘Limits to Growth.’ Ecological economist Daly (1978, 1996) advocated the concept of a steady state economy, which in contrast to the classical economics concept of the stationary state, is framed as a deliberate political action to create a steady economy made of constant stock of wealth (various forms of capital, including natural capital) and population size. Georgescu-Roegen (1971) applied the thermodynamic concept of entropy to economic analysis, arguing that all natural resources are irreversibly degraded through economic activity. Daly (1996) attempted to quantify these entropy limits through the concept of net primary productivity (the solar energy captured by plants and other photosynthetic organisms minus that used by the organisms themselves for respiration) as an input limit of the economy. Ehrlich and Ehrlich (1981) developed the concept of biodiversity limits based on the idea of species extinction and biodiversity loss as a possible limit to human population and economic growth. The concept of the planetary boundaries (Folke et al., 2009; Steffen et al., 2015) is the latest of such theoretical approaches that seek to define boundaries for growth through the notion of limits or thresholds that if exceeded could push humanity off the brink of the safe operating space known as the Holocene.

As goals and priorities are re-defined and put forward in global sustainability and resilience frameworks such as the UN Millennial Development and Sustainability Goals, the UNFCCC Paris Agreement on Climate Change, the UN Agenda 21, the (UNISDR, 2015a) Hyogro Framework for Disaster Reduction (2015–2030), etc., a clear trend can be observed in the conceptualization of economic growth and its effects on both the biophysical and the social environment and the use and distribution of resources: natural, financial, manufactured, social and human capital. Traditional economic growth theoretical models do not include natural capital except the availability of non-renewable fossil fuels and minerals. Known collectively through terms like the *environmental Kuznets curve* tradition and *'trickle-down theory,'* they posit that equity is a deterrent for growth and efficiency (Okun, 1975) and that initial inequality is both a natural byproduct of growth as well as a necessary factor to generate growth. Accordingly, economic growth follows a cycle where wealth generated at the top eventually 'trickles down' to the poor. Similarly, the literature builds on empirical studies that show the relationship between economic growth and adverse environmental impacts as an inverted U shape.

Criticism of this conceptualization of growth, spurred a new perspective termed *pro-poor growth* in the economic literature on development. It takes basis in the idea that growth alone will not benefit the poor, so strategies aimed at enhancing economic growth must intentionally focus on reducing poverty (Kakwani et al., 2004).

Over the past decade, a formidable amount of literature has emerged theoretically and empirically showing that the traditional economics claim that equity slows down growth is unsupported, and that inequality actually hinders growth (Berg & Ostry, 2011; Eberts et al., 2006). Moreover, inequality of all kinds (economic, political, and cultural) is seen to erode social cohesion and willingness to cooperate to protect common resources such as ecoservices (Cushing et al., 2015).

The most recent attempt to redefine growth and measure social welfare is the notion of *inclusive growth* (related terms include *inclusive wealth, inclusive economies*), which like pro-poor growth takes theoretical basis in arguing that equity is good for the economy. It focuses not only on the conditions of the poor but on the relative conditions of both poor and non-poor, arguing that all members of society should be able to contribute to and benefit from economic growth. Two schools of thought focus on inclusive growth from an outcome and process perspective, respectively. When growth is seen as an outcome, the focus is on the view that growth should benefit all members of society expressed through low-income inequality as well as non-income measures of well-being such as access to health and educational services (Thorat & Dubey, 2013). The process perspective of growth emphasizes the creation of opportunities and access to greater participation in the economy (Ali & Zhuang, 2007).

In Figure 21(a) cluster map of the literature on inclusive growth and related terms such as inclusive wealth and inclusive economy is given. It is difficult to ascertain any distinct knowledge domains from the three clusters, as the majority of terms that appear on the map are completely generic and non-context specific. We interpret this map as evidence for the primarily ideological nature of the concept. Inclusive growth, at least at present, is a rhetorical instrument for articulating particular policy goals; it is not a scientifically operational concept, with explicit theory and methodology.

Finally, two alternative perspectives of growth – *de-growth* and *a-growth* must be mentioned as of particular relevance to the field of ecological economics. Stressing the negative rather than the positive sides of growth, the de-growth perspective has a long tradition in the environmental activism domain. Its goal is to downscale production and consumption, and in some cases stop economic activity altogether, in order to decrease adverse anthropogenic impacts on the environment (e.g., Georgescu-Roegen, 1977; Kallis, 2011; Latouche, 2009; Martinez-Alier, 2009; Schneider et al., 2010).

A-growth is the less radical, precautionary position between pro-growth and de-growth. It posits that GDP is not a good indicator of social welfare as it estimates only the costs and not the benefits of market-related activities and does not include informal or non-market activities such as the use of natural resources and ecoservices (van den Bergh, 2011). A-growth theorists argue that policy should be directed towards correcting market inefficiencies that create environmental problems, ensuring that economic growth does not compromise the sustainability of life-supporting ecosystems (Crépin & Folke, 2014; van Den Bergh & Kallis, 2012).

We turn now to an examination of some proposed metrics in the context of re-evaluating the concepts of wealth and growth.

The traditional indicator for measuring economic growth is the Gross Domestic Product (GDP), which was developed by economist Simon Kuznets in the

United States in the context of finding a measure for the nation's productivity in the aftermath of the Great Depression (Kuznets, 1934). Although criticized strongly over the past decade for not being a good indicator for social welfare, the GDP nevertheless provides a good aggregate measure of productivity. Rackwitz (2002) argues that it 'provides the infrastructure of a country, its social structure, its cultural and educational offers, its ecological conditions among others but also the means for the individual enjoyment of life'. Faber et al. (2019) similarly argue that health and literacy are implicitly captured by the GDP as their development is facilitated by economic development and growth, which is adequately measured by the GDP.

The most widely used indicator to measure development is probably the United Nation's Human Development Index (HDI), which is based on the average of three other demographical indices: the GDP, the Education Index (EI) and the Life Expectancy Index (LEI).

Following the same principle of coupling economic growth and human development, Nathwani et al. (1997) developed the so-called Life Quality Index (LQI) to facilitate the development of societal risk acceptance criteria. The model takes basis in the philosophical idea that the only available resource to humans is time and that a model of life quality must reflect the time available to individuals in good health. The LQI is a utility function that represents societal preferences for trade-offs between life expectancy, time spent at work vs. leisure and GDP per capita invested into health improvement. Faber et al. (2019) apply the LQI in their methodological framework for a joint assessment of risk, sustainability and resilience.

New approaches and measures of social welfare that propose to do away with the GDP include the Happy Planet Index, the Inclusive Wealth Index and the Social Opportunity Function. The Happy Planet Index, introduced by the New Economics Foundation in 2006 is also based on the utilitarian principle of maximizing well-being in good health and longevity. It is calculated as a function of a given country's subjective life satisfaction, life expectancy at birth and ecological footprint per capita. On the positive side, the HPI contributes to the study of economic growth in that it attempts to measure the positive consequences of growth, namely well-being and health. It has also met with some strong criticism about the subjectivity of life satisfaction reporting, the controversiality of the footprint concept, which narrows its usage, and not least using the term happiness to measure not happiness but rather the degree of environmental efficiency supporting well-being.

Since 2012, the UN Sustainable Development Solutions Network has been publishing an annual World Happiness Report. Variables used to calculate a given country's happiness score include: GDP per capita, social support, healthy life expectancy, freedom to make life choices, generosity, and perceptions of corruption.

The Inclusive Wealth Index (IWI) is a joint initiative of the UN University International Human Dimensions Programme, the UN Environmental Programme

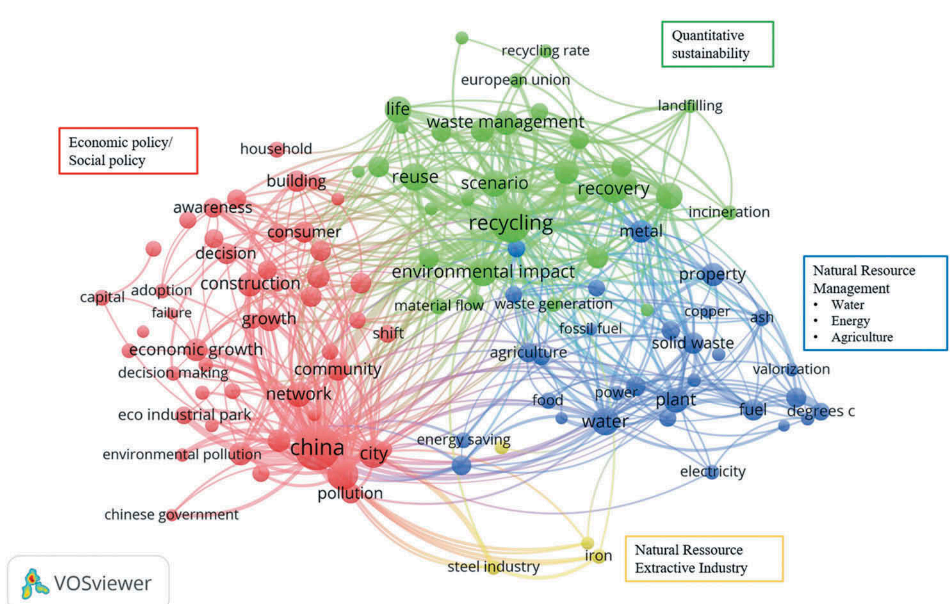

Figure 22. Network map of research on the concept of circular economy.

(UNEP) and the UN Educational, Scientific and Cultural Organization (UNESCO). It measures the wealth of a given country in terms of progress, well-being and long-term sustainability. Inclusive wealth is the aggregate sum of the social value of manufactured, human and natural capital. One significant innovation behind the effort to measure inclusive wealth is to try to disassociate the market value of goods and services from their wider social value in a societal context and attempt to measure the latter. Another one is the attempt to measure the stock of wealth-inducing conditions rather than flows of wealth (as the GDP does) thereby providing an inter-generational understanding of wealth and wellbeing. Nevertheless, the IWI has met with strong criticism based on theoretical assumptions, gaps in data availability, and inability to account for distributional issues (Roman & Thiry, 2016).

Finally, Ali and Son (2007) propose the Social Opportunity Function as a relevant measurement for inclusive wealth. They argue that inclusive wealth leads to the maximization of the social opportunity function. The increase of the latter depends on (i) average opportunities available to individuals in society and (ii) how these opportunities are shared or distributed. A particular weighting scheme that assigns greater weight to opportunities created for the poor ensures that growth is inclusive thus expanding not only average opportunities but improving their distribution among the population.

4.5.4. The concept of circular economy

While all organizations, public or private, aim to create value through their activities or business models, the concept of value creation has different meaning for different stakeholders and in different contexts. A common measure for value is the value that the stock market gives a company, i.e., market value. Value can also be expressed in terms of the value in a balance sheet, which is the accounting or book value of a company's assets minus its liabilities. Value can have different temporal dimensions as in the value based on expected future performance. In financial terms, value creation is the revenue (return on investment) that exceeds expenses (costs of capital). Traditional methods for assessing organizational performance are based precisely on profit and asset bases. A traditional model of value creation is a function of economies of industrial-scale characterized by mass production, high efficiency of repeatable tasks and constant, hierarchical structures of organization. Risk management in such a context is not much different from accounting.

Introducing contextual factors to value creation such as sustainability and resilience considerations does not disregard the relevance of financial value but it exposes its insufficiency. Thus, the notion of value creation has shifted over the past two decades to include a wide range of interactions and cause–effect relationships that take place in a market, regulatory, societal and environmental contexts. Organizational performance is now evaluated based on human social and natural capital than simply on profit and asset

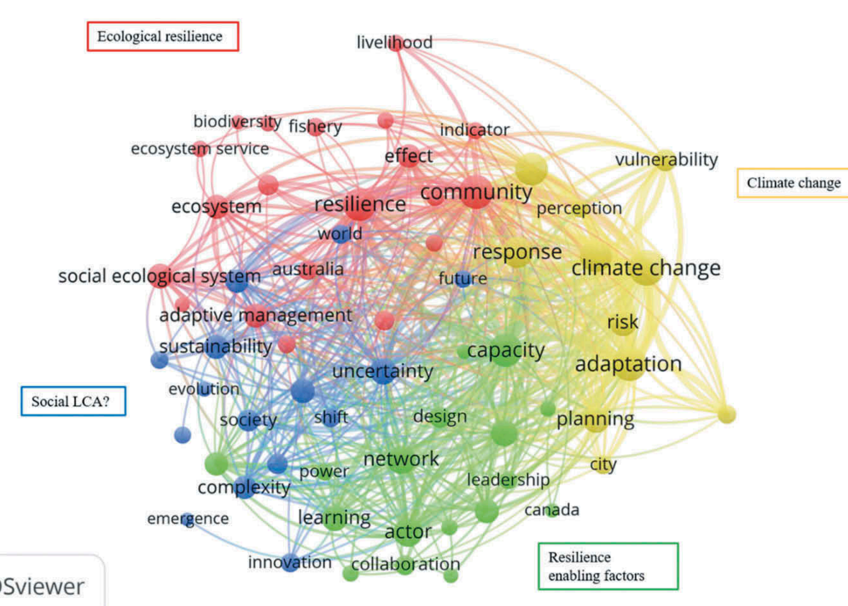

Figure 23. Network map of research on the concept of adaptive governance.

bases. Assets contributing to value creation are therefore not only tangible assets but also intangible, e.g., innovation, ideas, talent, reputation, well-being, etc. From mass production based on economies of scale, value is now created through mass customization, contextualization and creativity, favoring network rather than hierarchical organizational structures that are fluid, dynamic and capable of reconfiguration. Risk management similarly has had to be adapted to fit redefined perceptions of value creation through considering new, integrated frameworks for risk analysis, and going beyond traditional cost-benefit analysis of direct consequences with identifiable market values to consider both direct and indirect consequences of risk for which market values are not readily available (e.g., many environmental and social consequences).

At the same time, introducing concepts such as the circular economy into strategic risk management and governance is presently changing best practices in how risks are assessed and mitigated across industries and sectors. The new model of value creation rests on four crosscutting principles: (i) extending the use-cycle length of an asset, (ii) increasing the utilization of an asset or resource, (iii) looping or cascading an asset through additional use cycles, and (iv) regeneration of natural capital (WEF, 2015). The technocratic solution for enabling the new value business models rests on continuous development and implementation of smart technologies whereby the latter enhance knowledge about the location, condition and availability of assets, which in turn adds value to the product or service.

Unlike the concept of inclusive growth/wealth, the concept of circular economy takes scientific basis in quantitative sustainability. In Figure 22 four distinct clusters can be identified. The red cluster is the policy and governance cluster, which combines socio-economic considerations of sustainability. The closely related green (Quantitative Sustainability) and blue (Energy, Water and Agriculture) clusters relate to various aspects of Environmental engineering and natural resource management. The small and largely disconnected yellow cluster represents the extractive raw materials industry.

4.5.5. The concepts of adaptive governance and social ecological systems

The strategic principles for managing risk in accordance with sustainability and resilience considerations is first and foremost a governance issue. Governance and management are not the same but to be effective they require coherence and unison between them. Governance can be understood as the institutional arrangements in society that shape the decisions and behavior of societal stakeholders. Institutional arrangements can be understood as rules and norms (Ostrom, 2005). Management, on the other hand, explicitly refers to the processes of decision-making that involve the distribution of resources. In the following, the trend of transitioning from governance based on centralized expert management to adaptive governance is outlined. Principles and attributes of adaptive governance are briefly explained, and the conceptual framing of adaptive governance is critically discussed in the context of its application to risk, sustainability and resilience.

In Figure 23 Adaptive Governance is visualized. The map has four clusters. The yellow cluster is unified around the concept of climate change. We find it difficult to make sense of the other three clusters. It could be argued that all nodes in the other three clusters represent aspects of Policy. In the red cluster, we see resilience from an ecological and perhaps long-term perspective. In the blue cluster, social systems seem to appear through notions of Sustainability, Innovation, World. We label this cluster with hesitation Social LCA. The green cluster is also in the human/social realm of leadership, learning, collaboration, design, power, and capacity, or in other words factors that enable resilience.

Although the term *adaptive governance* is relatively new, it draws on extensive scholarship in the field of ecology, particularly the *adaptive management* notion as 'active' scientific hypothesis testing 'in the field' in the context of social-ecological systems proposed by Holling (1978) whereby management interventions are treated as experiments from which both managers and scientists can learn and adapt. The notion of panarchy was subsequently developed (Gunderson & Holling, 2002) as a possible framework describing stability and change dynamics in complex systems through a nested set of adaptive cycles (analogous to birth, growth, maturation, death, and renewal). Resilience is then explained through the adaptive cycle process and interactions among fast and slow variables that affect the adaptive cycles (Gunderson, 1999; Plummer, 2009).

Another line of scholarship on adaptive governance focuses on the study of cooperative strategies for the management of common pool resources (Carlsson & Berkes, 2005; Olsson et al., 2004; Folke et al., 2005; Plummer, 2009; Ostrom, 1990, 2010; Dietz et al., 2003). Key notions here include the concept of co-management as a dynamic, multi-level and policy-centric process that tries to achieve a balance between centralized and de-centralized control through the integration of local knowledge and formal scientific knowledge of natural resource systems and social-ecological systems inter-relations.

Adaptive governance is also studied in the context of collaborative governance of environmental problems

(Holley, 2010; Holley et al., 2011; Sabatier et al., 2005; Wondolleck & Yaffee, 2000), natural hazards management (Djalante et al., 2013), sustainability (Folke et al., 2005; Hatfield-Dodds et al., 2007), participatory civic democracy (Brunner et al., 2005; Dorf & Sabel, 1998; Freeman, 1997–1998) and adaptive experimental learning (Dewey, 1948/1920]); Holling 1978; Walters, 1986).

There is no formal definition of adaptive governance as it draws from various knowledge bases and is applied across a spectrum of concerns. Schultz et al. (2015) provide a general description, which could then be adapted to the different contexts of natural, human and social capital: 'Adaptive governance refers to flexible and learning-based collaborations and decision-making processes involving both state and non-state actors, often at multiple levels, with the aim to adaptively negotiate and coordinate management of social-ecological systems and ecosystem services across landscapes and seascapes.'

In order to understand the common principles and attributes of adaptive governance whether applied to ecosystems or social systems or a combination thereof, a contrast is made with the traditionally applied mode of management, namely that of the 'centralized expert management'. Critics of the traditional approach (Brunner et al., 2005; Dietz et al., 2003-Folke et al., 2005; Holling, 1978; Ostrom, 1990, 1999; Walker & Salt, 2006) have argued that the top-down, centralized institutional arrangements, which typically rely on reductionist science, may work for engineering problems and strictly controlled systems but are inadequate in the context of complex social-ecological systems. Hatfield-Dodds et al. (2007) locate adaptive governance in the middle of the spectrum, between centralized expert management and what they call 'romantic agrarianism' (a form of management that resonates with the de-growth governance philosophy). Adaptive governance is different from the other two types fundamentally because it is based on a philosophy of holism and systems science as opposed to that of reductionism. Unlike centralized expert management, which is based on silo disciplinary scientific knowledge, or romantic agrarianism, which only recognizes local traditional knowledge and customs, adaptive governance is about integrating different types of sources and knowledge that would add value to decisions. In this respect, adaptive governance is fully compatible with the notion of risk-informed decision support vs. the technocratic risk-based approach.

The state-managed approach derives its source of power and legitimacy through externally imposed government powers and resources implemented through carrot and stick policies in the belief that individuals are generally uncooperative. Targets are met through re-aligning the incentives of the resource users under the assumption that individuals are principally motivated by self-interest. Self-reliance and self-sufficiency (values cherished by the agrarian romantics) have no place in such a governance system. The relationship between policy and science in the technocratic model can be described as one where politicians use scientific experts as tools for behavior control.

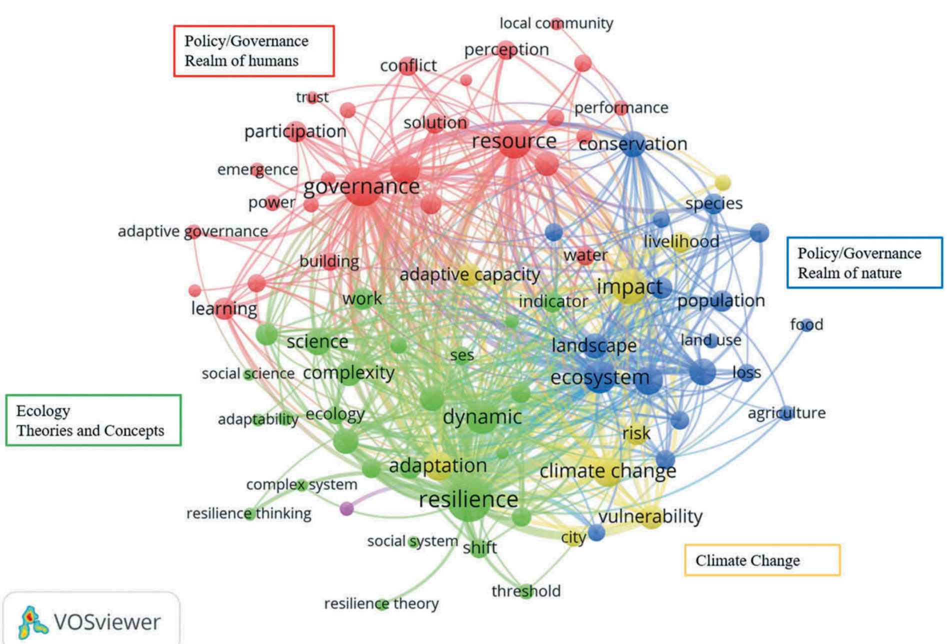

Figure 24. Network map of research on the concept of social ecological systems.

Adaptive governance, through its inclusion of multiple groups of interests from both state and non-state actors, derives its source of authority and legitimacy on the basis of multiple sources of participation and open civic democratic process of decision-making which is typically bottom-up. It attributes a mix of motives, including self-interest and regard for others, and grants individuals the capacity for cooperation and self-organization. The power dynamics in this system of governance are based on respect, trust and cooperation – all elements of the degree of social capital in a given society. The role of the scientific expert is seen as that of learning partner and facilitator on par and in cooperation with local practitioners and governance representatives. Reductionist scientific methodologies are not applicable in such an open and evolving context. Instead, continual trial and error experiments are advocated that can be replicated locally for faster and more effective learning thereby facilitating solutions to problems that are evolving and context-specific.

Learning is key to the concept of adaptive governance as it is seen as the capacity (social or natural) to respond to changes in a way that ensures survival and thriving, both literally and metaphorically. Social and transformational learning are explicit aims in adaptive governance and management.

How social learning is understood and defined depends on the epistemological tradition in the various application areas that have adopted the concept. Ison and Watson (2007) define social learning 'as achieving concerted action in complex and uncertain situations.' Reed et al. (2010) critique the misuse of the concept of social learning has been misused to describe not social learning itself but the conditions that enable it, i.e., stakeholder participation. They distinguish furthermore between social learning as an outcome and as a process, and clarify differences between individual and social learning. For them social learning is a type of practical learning by doing based on experience, and successful group processes based on the social interactions among the actors involved. Social learning implies a change in understanding in the individuals involved in-group learning, but this change goes beyond the individual and becomes embedded within wider social units. Ison et al. (2013) provide an analysis of metaphoric clusters associated with social learning, identifying seven semantic domains: performance, action, governance mechanism, balancing act, paradigm, cognition, and communication.

Social learning in the context of governance of social ecological systems should be understood as a governance mechanism as well as a set of practices that favors collaborative learning arrangements of different stakeholders and different types of knowledge, emphasizing participation, negotiation and team performance. Social learning unsurprisingly helps build social capital, or those social relations of trust, reciprocity and engagement that are said to be key for developing the adaptive capacity that makes systems resilient.

Folke et al. (2005) elaborate on what they consider the critical factors of the social sources of resilience that are instrumental in securing a system's integrity during periods of disturbance, change and transformation. *Social memory* has a central role in this process. In the present context, social memory can be understood as the collective experience of past disturbance events and the responses to those both on part of the community and the responsible governance structures. Social memory is thus the 'lessons learned, linking past experience and future adaptive response' (Folke et al., 2005). The effectiveness of social memory is

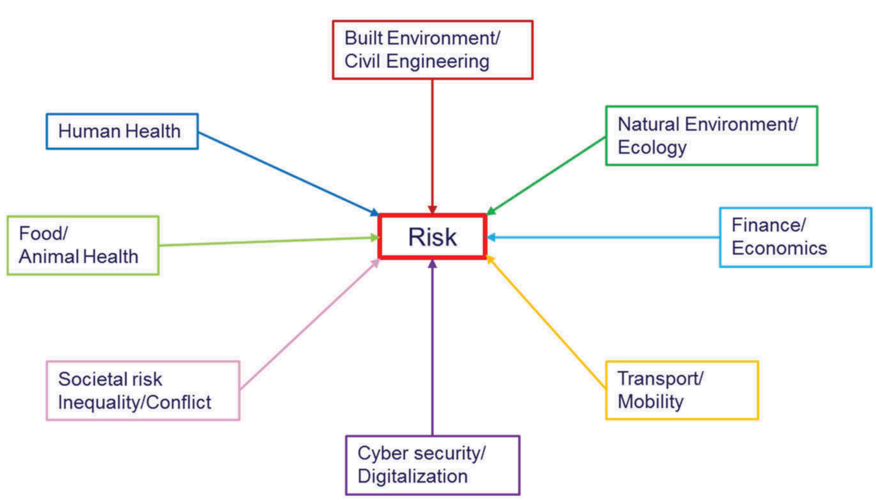

Figure 25. Illustration of disciplines and application areas where risk-informed decision-making is typically applied from a disciplinary or more rarely interdisciplinary perspective.

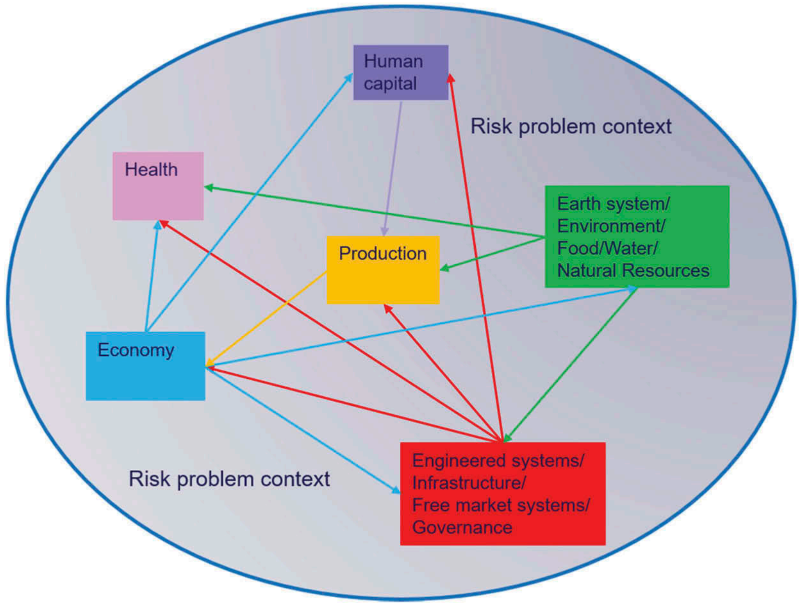

Figure 26. Illustration of necessary trans-disciplinary perspective for the integration of sustainability and resilience into risk (adapted from Faber 2018).

facilitated through different actors and teams of actors who all have distinct roles in getting a social network to respond and collaborate in the face of a disturbance, emphasizing the importance of diversity in the social fabric composition from diverse knowledge bases and practices to diverse psychological and personality traits of the group. Experimental studies of collaborative (learning) environments show that team size, newcomers and previous alliances all affect group performance (Guimerá et al., 2005) and that in the process of collaboration distinct roles such as leaders, critics, knowledge generators, knowledge transmitters, stewards, interpreters, visionaries, innovators, experimenters, followers, and reinforcers spontaneously emerge and organize (Folke et al., 2003; Gladwell, 2000; Holling & Chambers, 1973; Olsson et al., 2004).

In an overall strategic framework aiming to enhance the resilience of a given system, adaptive governance can be viewed as the strategic direction in pursuit of the goal, while growing learning institutions, based on social learning and experimental, in-context problem-based learning would be the means to strategy.

Finally, we consider the concept of Social Ecological Systems. On the map in Figure 24 we see four distinct clusters and a pink single node. The node stands for Social Ecological Resilience, and we have incorporated it in the green cluster. The green and red clusters share almost the same size, but the link strength of the green cluster is closer. The red cluster is the social/policy cluster of humans (governance, learning, participation, conflict, perception, resource) while the green is the theoretical or conceptual ecological domain (e.g., SES, resilience, adaptability, threshold, shift). The blue cluster is the non-human natural capital cluster (land use, landscape, ecosystem, species, conservation). The yellow cluster with nodes spreading all other three clusters is climate change.

Our interpretation and conclusion from comparing the maps in Figures 23 and 24 are that the apparent absence of the Engineering knowledge domain in issues pertaining to policy and governance and the strong dominance of the Ecological domain comes from the lack of ability of Engineering to position itself as a strategically relevant discipline influencing the long-term direction of research due to its myopic focus on operational and tactical issues. The implications for Engineering risk-resilience-sustainability decision support are that the Engineering knowledge domain faces the danger of being marginalized as a contributing body of knowledge by the more strategically and ideologically related realms of Environmental sciences and Ecology.

5. Implications for education

As a result of integrating resilience and sustainability considerations into risk assessment and management, new concepts have been formulated which go beyond disciplinary or even multi-disciplinary boundaries and are instead truly trans-disciplinary in nature, e.g., social ecological systems, circular economy, planetary boundaries, inclusive growth, adaptive governance, etc. At the

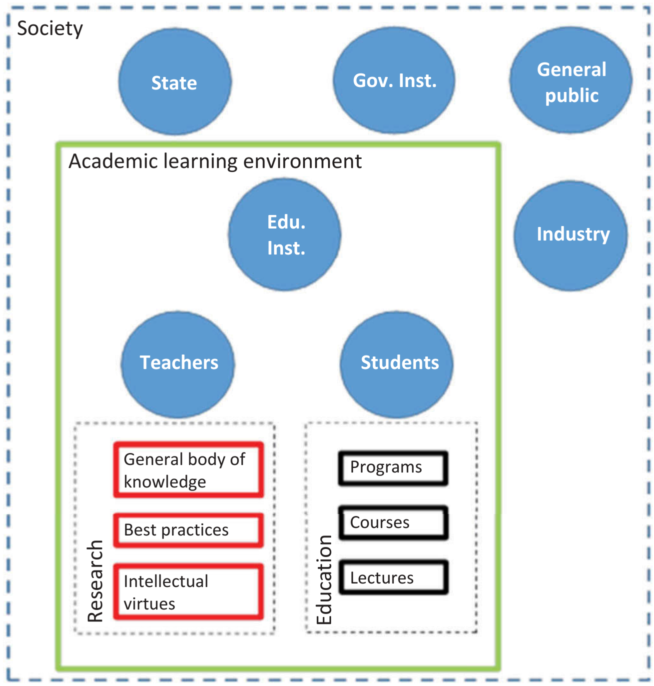

Figure 27. Illustration of main stakeholders (blue circles), assets (red frames) and instruments (black frames) in future risk education (Faber & Nielsen, 2017).

forefront of research are studies aiming at joint operational methodologies for risk, sustainability and resilience, accounting further for possible trade-offs among stated societal preferences. The bibliometric trends analyzed in this paper, together with a survey[2] of existing risk education programs have revealed that there is a significant gap between research and education, where education in the area of risk is stuck somewhere in the 1990s at best in terms of the disciplinary content (scientific theories and methods) as well as the classification of risks according to sector-specific or discipline-specific procedural models. Figure 25 shows the disciplinary view of risk, which at present is how the vast majority of risk educational programs are organized.

From the disciplinary and occasionally multidisciplinary perspective, risk education typically has the following components, taught more or less in the same sequence:

- Sources of risk in discipline X
- Regulative frameworks in X
- Procedural models for Risk Assessment in X (typically, assessment and management are separated through formal regulative frameworks as is the case in e.g., Environment and Food so that no political bias can enter the 'scientific' assessment of risk or an informal separation of quantitative 'hard' science vs. qualitative 'soft' managerial practice as is the case in e.g., Built Environment, Transport, Economics, etc.)
- Procedural model for Risk Management in X
- Scientific models in X (theories and methods)
- Data and metrics in X

When we compare this with the trans-disciplinary perspective, which the integration of sustainability and resilience into risk necessitates (Figure 26), we realize that our educational practice is simply inadequate due to the complexity of interactions and dependencies among engineered, natural and social systems.

To define any particular risk, its networked structure and the extent and strength of dependencies must first be identified within a system's boundary. Only after such trans-disciplinary and trans-sector system identification is performed can we begin to discuss theories, models, methods, metrics, and regulative constraints. Seen in this trans-disciplinary perspective, all risks are decision problem contexts and systems in and of themselves. They are furthermore complex systems because they are dynamic, evolving and have non-linear dependencies. Knowledge about a risk decision context cannot be known to the teacher a priori nor can it be taught as it is traditionally done through a curriculum that is based on the transmission from teacher to students of theories and methods to be applied to pre-identified and structured problems. Knowledge in the domain of risk is liquid and trans-disciplinary. By liquid, it is meant that the focus is on problem scenarios that could be taken in any order rather than on the notion of solid content that follows a pre-determined sequence (Savin-Baden, 2008). By trans-disciplinary it is meant that different disciplinary perspectives are merged together, resulting in new knowledge, which is co-created by all participants. In this sense, it is also a product of transitional and social learning, which are at the root of the adaptive capacity that fosters resilience on both the individual and the collective levels.

In addition to the trans-disciplinary and liquid characteristics of the knowledge environment of risk, a design for risk education must be informed by stakeholder engagement, social responsibility and the acquisition of both intellectual and civic values. As an applied discipline, risk must ensure that in educating future practitioners, a professional code of ethics must be adapted for the risk professional, modeled in principle after the Hippocratic oath future professionals in the medical field must adhere to (First, do no harm). As such, the design for risk education must formulate learning objectives, based on societal needs and preferences rather than narrow individual interests or industry preferences that are not in harmony with societal goals for sustainable development. In Figure 27 a system representation of the knowledge environment in which risk operates is given as an outline of the system boundary for a future design of risk education. It can be seen that education and research go together and that the general body of knowledge has to be developed continuously, with new findings and insights from the research community finding way into practice and educational activities. However, it is also important to appreciate that even in areas of education where the research front is not moving, or moving very slowly, there is a tremendous task for the educational institutions in preserving the already available knowledge.

The design basis for risk education should build on the theoretical foundations from systems thinking, Bayesian decision analysis, research problem-based learning, and transitional and social learning. As such, risk education will be based on the integration of multiple disciplinary perspectives, the inclusion and participation of stakeholders representing different societal sectors in the processes of establishing the risk problem context. The production of knowledge and the process of learning will be a joint endeavor of academic subject expertise, pedagogical facilitation and student active learning through inquiry-based project work.

Box 1. Key conclusions from bibliometric analysis.

- All 3 domains – risk, sustainability and resilience show an upward trend in production of research. Risk is dominant field. There is some integration between risk and sustainability and between risk and resilience. Research combining all three is in its infancy.
- The top 3 contributing disciplines are: (i) Environmental Sciences/Ecology, (ii) Engineering, and (iii) Economics representing, respectively, ecological, engineered and social systems perspectives.
- Risk research over the last 30 years has undergone a transformation from a predominantly decision theoretical/Civil Engineering perspective toward an environmental/ecological perspective. The traditional Engineering area of Health and Safety (OHS) has been strongly marginalized. New areas of research have gained importance: Climate Change, Natural Hazards, Food Safety.
- Research in sustainability and resilience is dominated by the developed western countries (USA, the UK, Canada, Australia, and Sweden). China is a major contributor to quantitative sustainability and circular economy research.
- Despite lower output of research in comparison with the Environmental Sciences/Ecology knowledge domain, the centrality of the Engineering knowledge domain in the network representations could be interpreted as the Engineering systems perspective affording a potentially unifying role among the 3 systems perspectives. The success criteria for living up to such a role would be the integration of risk, resilience and sustainability into joint strategic, operational and tactical frameworks for assessment, management and education.

6. Conclusion

The ability of notions such as risk, resilience and sustainability to integrate within conceptually different knowledge domains has promoted their diffusion across a wide range of disciplinary areas. As descriptors of desirable and undesirable system states across biotic lifeworlds and man-made built environments, they can be found in every activity we seek to acquire knowledge about that may assure our continued existence and well-being. The systematic scientific study of risk has a significantly longer history than that of resilience and sustainability, dating back to the evolving understanding of probability since the 17th c. that allowed predicting future events and the resulting empowerment to make deliberate decisions based on informed choices. The application of probabilistic methods has since driven capital markets, insurance, industrial development, transport, and healthcare. Since the second half of the twentieth century, the knowledge domain of risk has broadened to include theoretical and empirical behavioral aspects of decision theory, game theory, and neuro-cognitive sciences.

While in the second half of the twentieth century the field of risk was characterized by a narrow technocratic and expert-driven assessment of risk, a fundamental shift was initiated at the turn of the millennium as a response to a policy demand for pragmatic, evidence-based decision support that would legitimize the decision-making process by making it more transparent and participatory, and, at the same, take explicit consideration of sustainability and the optimization of scarce natural resources. Integrated risk management frameworks were promoted across public and private sector organizations and academia, calling for an explicit consideration of the interaction between all relevant agents – technical and structural elements, nature, humans and organizations – in the assessment of the risks associated with a given system. The idea of integrated risk management offered a contrast to the previous technocratic approach. It advocated a holistic perspective not only in terms of considering multiple risks through a portfolio approach (a so-called *all hazards approach*) but also taking time into consideration. This meant that risk assessment should be performed to consider all phases of the life of a system, from the early design phase to the end of the service life, including decommissioning. Furthermore, economic development in the present time should not jeopardize the ability of future generations to meet their needs (WCED, 1987). In the disciplinary domain of environmental risk assessment and management and related Life Cycle Assessment methodologies, this concept was popularized through the term 'cradle to grave' approach. Once established as a normative sustainability goal, it quickly spread to other disciplines and industrial sectors, e.g., 'farm to fork' – in the context of human and animal health, but was soon to be replaced by the 'cradle-to-cradle' philosophy that has now come to epitomize the principles behind the concept of circular economy that is presently a strong normative component of sustainable growth. But while the sustainability discourse entered the risk domain largely through economic considerations of efficiency and optimization of scarce resources and ethical considerations of inter-generational justice, thus bringing the technical aspects of risk assessment closer together with the socio-economic aspects of risk management, resilience was more a qualitative reformulation of a concept that was already part of the risk knowledge domain; namely, robustness. Over the past 30 years, the notion of resilience, with its firm roots in ecology, became transplanted and adapted to the risk domain, resulting in an explosion of academic and gray literature. Risk, formerly studied and taught primarily as a specialization in civil engineering, economics and finance or through the lens of safety in transport and industries such as oil and gas, mining and petrochemicals, has become a much broader knowledge domain that could be seen as a discipline in its own right.

As a result of incorporating resilience and sustainability considerations in the assessment and management of risk, the systems of interest have also expanded in scale from mainly closed industrial engineered systems to open social-ecological systems. Problematically, not all theories and methods can be exported from one knowledge domain to another, creating both strategic challenges for risk governance and operational challenges for risk management. Educational objectives and methods must be re-evaluated to align with both academic research and societal needs.

The principle aim of this study has been to bring order among the multiplicity of concepts and perspectives that join research and discourse on risk, resilience and sustainability through combining a transparent bibliometric analysis of the literature with a rich contextual qualitative description of established and emerging concepts. In the present study founded on an assessment report by the authors, based on 442,171 records and three decades of research, we show the historical evolution of the knowledge domains of risk, sustainability and resilience on a to-date unprecedented scale. Based on this assessment and more than 100 cluster network maps we illustrate the different disciplinary contributions, important authors, geographic distribution of the research, and the organizations producing the research.

Our main conclusions are summarized in Box 1.

The focus of the qualitative analysis has been to describe emergent concepts as a result of integrating resilience and sustainability considerations in the knowledge domain of risk as well as how such integration might impact future research and education. We have identified four characteristics of the knowledge environment relevant for the development of risk education (i) liquid knowledge, (ii) trans-disciplinarity, (iii) social responsibility and stakeholder engagement, and (iv) intellectual and civil society values. These characteristics call for a high level of plasticity in designing a learning environment that can accommodate both the dynamic nature of knowledge content and the dynamic engagement among multiple societal stakeholders. We conclude that a future learning design encompassing risk, sustainability and resilience must build on the theoretical principles of systems thinking, Bayesian decision analysis, inquiry problem-based learning and transitional learning.

Notes

1. Available at: http://vbn.aau.dk/files/286815989/Data_report_for_the_bibliometric_analysis_of_risk_sustainability_and_resilience_research_from_1990_to_2017.pdf.
2. A copy of the survey can be obtained by writing to the authors.

Disclosure statement

No potential conflict of interest was reported by the authors.

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References

Ali, I., & Son, H. H. (2007). Measuring inclusive growth. *Asian Development Review*, *24*(1), 11–31.

Ali, I., & Zhuang, J. (2007). *Inclusive growth toward a prosperous Asia: Policy implications* (ERD working paper series No. 97). Manila, Philipines: Asian Development Bank.

Allen, C. R., Angeler, D. G., Cumming, G. S., Folke, C., & Twidwell, D. R. (2016). Quantifying spatial resilience. *Journal of Applied Ecology*, *53*, 625–635.

Allen, C. R., Angeler, D. G., Garmestani, A. S., Gunderson, L. H., & Holling, C. S. (2014). Panarchy: Theory and application. *Ecosystems*, *17*, 578–589.

Anderies, J. M., Folke, C., Walker, B., & Ostrom, E. (2013). Aligning key concepts for global change policy: Robustness, resilience, and sustainability. *Ecology and Society*, *18*(2), 8.

Angeler, D. G., & Allen, C. R. (2016). Quantifying resilience. *Journal of Applied Ecology*, *53*, 617–624.

Angeler, D. G., Allen, C. R., Barichievy, C., Eason, T., Garmestani, A. S., Graham, N. A. J., Granholm, D., Gunderson, L. H., Knutson, M., Nash, K. L., Nelson, R. J., Nyström, M., Spanbauer, T. L., Stow, C. A., & Sundstrom, S. M. (2016). Management applications of discontinuity theory. *Journal of Applied Ecology*, *53*, 688–698.

Baland, J. M., & Platteau, J. P. (1996). *Inequality and collective action in the commons CRED, University of Namur*. Belgium: Mimeo.

Barabási, A.-L. (2009). Scale-free networks: A decade and beyond. *Science*, *325*, 412–413.

Barabási, A.-L. (2016). *Network science*. Cambridge, UK: Cambridge University Press.

Barrett, C. B., & Carter, M. R. (2013). The economics of poverty traps and persistent poverty: Empirical and policy implications. *The Journal of Development Studies*, *49*(7), 976–990.

Barrett, C. B., & Constas, M. A. (2014, October 7). Toward a theory of resilience for international development applications. *PNAS*, *111*(40), 14625–14630.

Barzel, B., & Barabási, A.-L. (2013). Universality in network dynamics. *Nature Physics*, *9*, 673–681.

Baum, S. D., & Handoh, I. C. (2014). Integrating the planetary boundaries and global catastrophic risk paradigms. *Ecological Economics*, *107*, 13–21.

Berg, A. G., & Ostry, J. D. (2011). *Inequality and unsustainable growth: Two sides of the same coin?* Washington, D.C.: International Monetary Fund.

Berkes, F., Colding, J., & Folke, C. (Eds.). (2003). *Navigating social–Ecological systems: Building resilience for complexity and change*. Cambridge, UK: Cambridge University Press.

Berkes, F., & Folke, C. (1992). A systems perspective on the interrelations between natural, human-made and cultural capital. *Ecological Economics*, *5*, 1–8.

Bishop, R. C. (1978). Endangered species and uncertainty: The economics of a safe minimum standard. *American Journal of Agricultural Economics*, *61*, 10–18.

Brundtland, G. H. (1987). *World commission on environment and development (1987). Our common future* (pp. 27). Oxford: Oxford University Press. ISBN 019282080X.

Bruneau, M., Chang, S., Eguchi, R., Lee, G., O'Rourke, T., Reinhorn, A., Shinozuka, M., Tierney, K., Wallace, W., & von Winterfeldt, D. (2003). A framework to quantitatively assess and enhance seismic resilience of communities. *Earthquake Spectra*, *19*, 733–752.

Brunner, R., Steelman, T., Coe-Juell, L., Cromley, C., Edwards, C., & Tucker, D. (2005). *Adaptive governance: Integrating science, policy and decision making*. New York: Columbia University Press.

WCED; Bruntland, G. H. (1987). *Our common future: Report of the 1987 world commission on environment and development*. Oxford, UK: Oxford University Press.

Carlsson, L., & Berkes, F. (2005). Co-management: Concepts and methodological implications. *Journal of Environmental Management*, *75*(1), 65–76.

Carpenter, S., Walker, B., Anderies, J. M., & Abel, N. (2001). From metaphor to measurement: Resilience of what to what? *Ecosystems*, *4*(8), 765–781.

Carson, J., & Doyle, J. (2000). Highly optimized tolerance: Robustness and design in complex systems. *Physical Review Letters*, *84*(11), 2529–2532.

Cifdaloz, O., Regmi, A., Anderies, J. M., & Rodriguez, A. A. (2010). Robustness, vulnerability, and adaptive capacity in small-scale social-ecological systems: The Pumpa irrigation system in Nepal. *Ecology and Society*, *15*(3), 39.

Ciriacy-Wantrup, S. V. (1952). *Resource conservation: Economics and policies*. Berkeley, CA, USA: University of California Press.

Costanza, R., & Daly, H. E. (1992). Natural capital and sustainable development. *Conservation Biology*, *6*, 37–46.

Crépin, A. S., & Folke, C. (2014). The economy, the biosphere and planetary boundaries: Towards biosphere economics. *International Review of Environmental and Resource Economics*, *8*, 57–100.

Crowards, T. M. (1998). Safe minimum standards: Costs and opportunities. *Ecological Economics*, *25*, 303–314.

Cumming, G. S. (2011). *Spatial resilience in social-ecological systems* (pp. 1–308). New York, NY, USA: Springer Science.
Cushing, L., Morello-Frosch, R., Wander, M., & Pastor, M. (2015). The haves, the have-nots, and the health of everyone: The relationship between social inequality and environmental quality. *Annual Review of Public Health*, *36*, 193–209.
Cutter, S. L., Ahearn, J. A., Amadei, B., Crawford, P., Eide, E. A., Galloway, G. E., Goodchild, M. F., Kunreuther, H. C., Li-Vollmer, M., & Schoch-Spana, M. (2013). Disaster resilience: A national imperative. *Environment: Science and Policy for Sustainable Development*, *55*(2), 25–29.
Dakos, V., Carpenter, S. R., Brock, W. A., Ellison, E. M., Guttal, V., Ives, A. R.,. . .& Scheffer, M. (2012). Methods for detecting early warnings of critical transitions in time series illustrated using simulated ecological data. *PLoS One*, *7*, e41010.
Daly, H. E. (1978). *Steady state economics: The economics of biophysical equilibrium and moral growth*. New York, NY: W. H. Freeman & Co.
Daly, H. E. (1996). *Beyond growth: The economics of sustainable development*. Boston, MA: Beacon Press.
Dasgupta, P. (2014). Measuring the wealth of nations. *Annu. Rev. Resour. Econ.*, *6*(1), 17–31.
Dasgupta, P., & Serageldin, I. (eds.). (1999). *Social capital: A multifaceted perspective*. Washington, D.C., USA: The World Bank.
Dawson, T. P., Jackson, S. T., House, J. I., Prentice, I. C., & Mace, G. M. (2011). Beyond predictions: Biodiversity conservation in a changing climate. *Science*, *332*(6025), 53–58.
Department of Homeland Security. (2013). *National infrastructure protection plan*. NIPP 2013: Partnering for Critical Infrastructure Security and Resilience, Washington D.C.
Dewey, J. (1948/1920). *Reconstruction in philosophy*. Boston: Beacon Press.
Dietz, T., Ostrom, E., & Stern, P. C. (2003). The struggle to govern the commons. *Science*, *302*, 1907–1912.
Djalante, R., Holley, C., Thomalla, F., & Carnegie, M. (2013). Pathways for adaptive and integrated disaster resilience. *Naturals Hazards*, *69*, 2105–2135. doi:10.1007/s11069-013-0797-5
Dorf, M. C., & Sabel, C. F. (1998). A constitution of democratic experimentalism. *Columbia Law Review*, *98*, 267–473.
Eberts, R., Erickcek, G., & Kleinhenz, J. (2006). *Dashboard indicators for the Northeast Ohio economy: Prepared for the fund for our economic future*. Cleveland, OH: Federal Reserve Bank of Cleveland.
Ehrlich, P. R., & Ehrlich, A. H. (1981). *Extinction: The causes and consequences of the disappearance of species*. New York: Random House.
Eisenberg, D., Linkov, I., Park, J., Bates, M., Fox-Lent, C., & Seager, T. (2014). Resilience metrics: Lessons from military doctrines. *Solutions*, *5*, 76–87.
Ekins, P., Simon, S., Deutsch, L., Folke, C., & de Groot, R. (2003). A framework for the practical application of the concepts of critical natural capital and strong sustainability. *Ecological Economics*, *44*(2), 165–185.
Faber, M. H. (2009). *Risk and safety in Engineering*. Switzerland: Lecture Notes, ETH.
Faber, M. H., & Nielsen, L. (2017). Value informed conception, design, implementation and operation of education and teaching activities. In M. Laban et al. (Eds.), *Book of Proceedings: 1st International Symposium K-FORCE 2017* (pp. 187–197). Higher Education Technical School of Professional Studies and University of Novi Sad, Faculty of Technical Sciences, Novi Sad, Serbia.
Faber, M. H. (2018). On sustainability and resilience of engineered systems. In P. Gardioni (Ed.), *Chapter 3 of Routledge handbook on sustainable and resilient infrastructure* (pp. 28–49). London: Routledge.
Faber, M. H., Qin, J., & Nielsen, L. (2019). Metrics and objectives in decision support for urban resilience. Submitted to ICASP 13, Seoul 2019.
Faber, M. H., & Rackwitz, R. (2004). Sustainable decision making in Civil Engineering. *Structural Engineering International*, *3/2004*, 237–242.
Faber, M. H., & Stewart, M. G. (2003). Risk assessment for civil engineering facilities: Critical overview and discussion. *Reliability Engineering and System Safety*, *80*, 173–184.
Faber, M.H. (2011). On the governance of global and catastrophic risks. *International Journal Of Risk Assessment and Management*, *15*(5-6), 400–416.
Fang, K., Heijungs, R., & de Snoo, G. R. (2015). Understanding the complementary linkages between environmental footprints and planetary boundaries in a footprint–Boundary environmental sustainability assessment framework. *Ecological Economics*, *114*(2015), 218–226. doi:10.1016/j.ecolecon.2015.04.008
Fiksel, J. (2003). Designing resilient, sustainable systems. *Environmental Science and Technology*, *37*(23), 5330–5339.
Folke, C., Colding, J., & Berkes, F. (2003). Synthesis: Building resilience and adaptive capacity in social-ecological systems. In F. Berkes, J. Colding, & C. Folke (Eds.), *Navigating social-ecological systems: Building resilience for complexity and change* (pp. 352–387). Cambridge, UK: Cambridge University Press.
Folke, C., Chapin, F. S., III, & Olsson, P. (2009). Transformations in social-ecological systems. In F. S. Chapin III, G. P. Kofinas, & C. Folke (Eds.), *Principles of ecosystem stewardship: Resilience-based natural resource management in a changing world.* (pp. 103–125), New York: Springer.
Folke, C., Biggs, R., Norström, A. V., Reyers, B., & Rockström, J. (2016). Social-ecological resilience and biosphere-based sustainability science. *Ecology and Society*, *21*(3), 41.
Folke, C., Carpenter, S. R., Walker, B., Scheffer, M., Chapin, T., & Rockström, J. (2010). Resilience thinking: Integrating resilience, adaptability and transformability. *Ecology and Society*, *15*(4), 20.
Folke, C., Hahn, T., Olsson, P., & Norberg, J. (2005). Adaptive governance of social-ecological systems. *Annual Review of Environment and Resources*, *30*, 441–473.
Folke, C., Jansson, A., Rockström, J., Olsson, P., Carpenter, S. R., Chapin, F. S., III, Crépin, A.-S., Daily, G., Danell, K., Ebbesson, J., Elmqvist, T., Galaz, V., Moberg, F., Nilsson, M., Österblom, H., Ostrom, E., Persson, Å., Peterson, G., Polasky, S., Steffen, W., Walker, B., & Westley, F. (2011). Reconnecting to the biosphere. *Ambio*, *40*(7), 719–738.

Folke, C. S., Carpenter, S. R., Walker, B. H., Scheffer, M., Elmqvist, T., Gunderson, L. H., & Holling, C. S. (2004). Regime shifts, resilience, and biodiversity in ecosystem management. *Annual Review of Ecology, Evolution, and Systematics*, *35*, 557–581.

Freeman, J. (1997–1998). Collaborative governance in the administrative state. *UCLA Law Review*, *45*(1), 1–98.

Ganin, A. A., Massaro, E., Gutfraind, A., Steen, N., Keisler, J. M., Kott, A., Mangoubi, R., & Linkov, I. (2016). Operational resilience: Concepts, design and analysis. *Nature Scientific Reports*, *6*(19540), 1–12.

Garvin, S. (2012). *Flood resilient building – Part 2: Building in flood-risk areas and designing flood resilient buildings*. Watford: BRE Press.

Georgescu-Roegen, N. (1971). *The entropy law and the economic process*. Boston, MA: Harvard University Press.

Georgescu-Roegen, N. (1977). Inequality, limits and growth from a bio-economic viewpoint. *Review of Social Economy XXXV*, *3*, 361–375.

Gersonius, B., Zevenbergen, C., van Herk, S., Kabat, P., Möltgen, J., & Pahl-Wostl, C. (2008). Managing flood risk in the urban environment: Linking spatial planning, risk assessment, communication and policy. *Adaptive and Integrated Water Management Adaptive and Integrated Water Management*, 263–275. doi:10.1007/978-3-540-75941-6_14

Gladwell, M. (2000). *The tipping point: How little things can make a big difference*. Boston, MA: Little Brown.

Guimerá, R., Mossa, S., Turtschi, A., & Amaral, L. (2005). The worldwide air transportation network: Anomalous centrality, community structure, and cities' global roles. *Proceedings of the National Academy of Sciences USA*, *102*, 7794–7799.

Gunderson, L. (1999). Resilience, flexibility and adaptive management—Antidoes for spurious certitude? *Ecology and Society*, *3*(1), Article No. 7.

Gunderson, L. H., & Holling, C. S. (Eds.). (2002). *Panarchy: Understanding transformations in human and natural systems*. Washington, DC, USA: Island Press.

Gunderson, L. H., Holling, C. S., & Light, S. S. (Eds.). (1995). *Barriers & bridges to the renewal of ecosystems and institutions*. New York, New York, USA: Columbia University Press.

Hartford, D. N. D. (2008, March). Legal framework considerations in the development of risk acceptance criteria, *Structural Safety*, *31*(2), Risk Acceptance and Risk Communication, 118–123. ISSN 0167-4730 (special ed. M. H. Faber).

Hatfield-Dodds, S., Nelson, R., & Cook, D. C. (2007, July 4–5). *Adaptive governance: An introduction, and implications for public policy*. Paper presented at the ANZSEE Conference, Noosa Australia.

Helbing, D. (2013). Globally networked risks and how to respond. *Nature*, *497*, 51–59.

Holley, C. (2010). Removing the thorn from new governance's side: Examining the emergence of collaboration in practice and the roles for law, nested institutions and trusts. *Environmental Law Reporter*, *40*(7), 10656–10686.

Holley, C., Gunningham, N., & Shearing, C. (2011). *The new environmental governance*. London: Routledge.

Holling, C. S. (1973). Resilience and stability of ecological systems. *Annual Review of Ecology, Evolution, and Systematics*, *4*, 1–23.

Holling, C. S. (1978). *Adaptive environmental assessment and management*. Chichester: Wiley-Interscience.

Holling, C. S. (2001). Understanding the complexity of economic, ecological, and social systems. *Ecosystems*, *4*, 390–405.

Holling, C. S., & Chambers, A. D. (1973). Resource science: The nurture of an infant. *BioScience*, *23*, 13–20.

Hollnagel, E. (2011). *Prologue: The scope of resilience engineering, in resilience engineering in practice: A guidebook*. Aldershot, UK: Ashgate.

Hollnagel, E. (2012) FRAM - The Functional Resonance Analysis Method, London: CRC Press, doi: https://doi.org/10.1201/9781315255071.

Hollnagel, E. (2014). Resilience engineering and the built environment. *Building Research and Information*, *42*(2), 221–228.

Hollnagel, E., Paries, J., Woods, D. D., & Wreathall, J. (2011). *Resilience engineering in practice: A guidebook*. London: Ashgate studies in resilience engineering.

Homer-Dixon, T., Walker, B., Biggs, R., Crepin, A.-S., Folke, C., Lambin, E. F., Peterson, G. D., Rockström, J., Scheffer, M., Steffen, W., & Troell, M. (2015). Synchronous failure: The emerging causal architecture of global crisis. *Ecology and Society*, *20*(3), 6.

Hughes, T. P., Gunderson, L. H., Folke, C., Baird, A. H., Bellwood, D., Berkes, F.,. . . & Nyström, M. (2007). Adaptive management of the great barrier reef and the grand canyon world heritage areas. *Ambio*, *36*(7), 586–592.

Huntjens, P., Pahl-Wostl, C., Rihoux, B., Schlüter, M., Flachner, Z., Neto, S., & Nabide Kiti, I. (2011). Adaptive water management and policy learning in a changing climate: A formal comparative analysis of eight water management regimes in Europe, Africa and Asia. *Environmental Policy and Governance*, *21*(3), 145–163.

ILCD. (2010, March). *European commission - Joint research centre - Institute for environment and sustainability: International reference life cycle data system (ILCD) Handbook - General guide for life cycle assessment - Detailed guidance*. First edition March 2010. EUR 24708 EN. Luxembourg: Publications Office of the European Union.

ISO 2394. (2015). *General principles on reliability for structures*. Geneva, Switzerland: International Standards Organization.

ISO 31000. (2018). *Risk management*. Geneva, Switzerland: International Standards Organization.

ISO 31010. (2009). *Risk assessment*. Geneva, Switzerland: International Standards Organization.

Ison, R., Blackmore, C., & Iaquinto, B. L. (2013). Towards systemic and adaptive governance: Exploring the revealing and concealing aspects of contemporary social-learning metaphors. *Ecological Economics*, *87*, 34–42.

Ison, R., & Watson, D. (2007). Illuminating the possibilities for social learning in the management of Scotland's water. *Ecology and Society*, *12*(1), 21.

Janssen, M., & Anderies, J. (2007). Robustness trade-offs in social-ecological systems. *International Journal of the Commons*, *1*(1), 43–65.

Jansson, A., Hammer, M., Folke, C., & Costanza, R. (1994). *Investing in natural capital: The ecological economics approach to sustainability*. Washington D.C.: Island Press.

JCSS. (2008). *Risk assessment in engineering, principles, system representation & risk criteria*. Zurich, Switzerland: The Joint Committee on Structural Safety.

Kakwani, N., Khandker, S., & Son, H. (2004). *Pro-poor growth: Concepts and measurements with country case studies international poverty centre working paper 1*, United Nations Development Programme International Poverty Centre, Brazilia, Brazil.

Kallis, G. (2011). In defence of degrowth. *Ecological Economics*, *70*(5), 873–880.

Kareiva, P., Tallis, H., Ricketts, T. H., Daily, G. C., & Polasky, S. (Eds.). (2011). *Natural capital: Theory and practice of mapping ecosystem services*. Oxford, UK: Oxford University Press.

Klammler, H., Rao, P. S. C. R., & Hatfield, K. (2016). *Resilience of urban communities: Coupled dynamics of infrastructure and institutions*. Submitted.

Kuznets, S. (1934). *National income 1929–1932*. New York: National Bureau of Economic Research.

Kuznetsov, Y. A., & Levitin, V. V. (1997). *CONTENT: A Multiplatform Environment for Continuation and Bifurcation Analysis of Dynamical Systems* (Centrum voor Wiskunde en Informatica, Kruislaan 413, 1098). SJ Amsterdam, The Netherlands.

Lansing, J. S. (2003). Complex adaptive systems. *Annual Review of Anthropology*, *32*, 183–204.

Latouche, S. (2009). *Farewell to growth*. Cambridge: Polity Press.

Liao, K.-H. (2012). A theory on urban resilience to floods – A basis for alternative planning practices. *Ecology & Society*, *17*(4), 48.

Linkov, I., Bridges, T., Creutzig, F., Decker, J., Fox-Lent, C., Kröger, W., Lambert, J. H., Levermann, A., Montreuil, B., & Nathwani, J. (2014). Changing the resilience paradigm. *Nature Climate Change*, *4*(6), 407–409.

Linkov, I., Eisenberg, D. A., Bates, M. E., Chang, D., Convertino, M., Allen, J. H., Flynn, S. E., & Seager, T. P. (2013a). Measurable resilience for actionable policy. *Environmental Science & Technology*, *47*(18), 10108–10110.

Linkov, I., Eisenberg, D. A., Plourde, K., Seager, T. P., Allen, J., & Kott, A. (2013b). Resilience metrics for cyber systems. *Environment Systems and Decisions*, *33*(4), 471–476.

Malthus, T. (1798). *An essay on the principle of population, as it affects the future improvement of society with remarks on the speculations of Mr. Godwin, M. Condorcet and other writers*. London: J. Johnson, in St. Paul's Churchyard.

Martinez-Alier, J. (2009). Socially sustainable economic degrowth. *Development and Change*, *40*(6), 1099–1119.

Meadows, D., Meadows, D. H., Meadows, D, L., Randers, J. & Behrens Ill, W. W. (1972). *The limits to growth*. New York, NY: Universe Books.

Meadows, D., Randers, J., & Meadows, D. (2004). *Limits to growth: The thirty year update*. White River Junction, VT: Chelsea Green Publishing Company.

Mens, M. J. P., Klijn, F., De Bruijn, K. M., & Van Beek, E. (2011). The meaning of system robustness for flood risk management. *Environmental Science and Policy*, *14*, 1121–1131. doi:10.1016/j.envsci.2011.08.003

Moore, C., Grewar, J., & Cumming, G. S. (2016). Quantifying network resilience: Comparison before and after a major perturbation shows strengths and limitations of network metrics. *Journal of Applied Ecology*, *53*, 636–645. doi:10.1111/1365-2664.12486

Nathwani, J. S., Lind, N. C., & Pandey, M. D. (1997). *Affordable safety by choice: The life quality method*. Waterloo: Institute for Risk Research.

Newman, M. E. J. (2006). *Networks - An introduction*. Oxford: Oxford University Press.

Nielsen, L., & Faber, M. H. (2018). *Data report for the bibliometric analysis of risk, sustainability and resilience research from 1990 to 2017* (DCE Technical Reports, No. 248). Aalborg: Department of Civil Engineering, Aalborg University. Retrieved from http://vbn.aau.dk/files/286815989/Data_report_for_the_bibliometric_analysis_of_risk_sustainability_and_resilience_research_from_1990_to_2017.pdf

Nyström, M., & Folke, C. (2001). Spatial resilience of coral reefs. *Ecosystems*, *4*, 406–417.

Øien, K., Massaiu, S., & Tinmannsvik, R. K. (2012). *Guideline for implementing the REWI method; resilience-based early warning indicators* (SINTEF report A22026). SINTEF Technology and Society.

Okun, A. M. (1975). *Equality and efficiency, the big tradeoff*. Washington, D.C.: Brookings Institution.

Olsson, P., Folke, C., & Berkes, F. (2004). Adaptive comanagement for building resilience in social-ecological systems. *Environmental Management*, *34*(1), 75–90.

Ostrom, E. (1990). *Governing the commons: The evolution of institutions for collective action*. Cambridge, UK: Cambridge University Press.

Ostrom, E. (1999). Coping with tragedies of the commons. *Annual Review of Political Science*, *2*, 493–535.

Ostrom, E. (2005). *Understanding institutional diversity*. Princeton, NJ, USA: Princeton University Press.

Ostrom, E. (2010). Polycentric systems for coping with collective action and global environmental change. *Global Environmental Change*, *20*(4), 550–557.

Park, J., Seager, T. P., Rao, P. S. C., Convertino, M., & Linkov, I. (2013). Integrating risk and resilience approaches to catastrophe management in engineering systems. *Risk Analysis*, *33*, 356–367.

Petschel-Held, G., Schellnhuber, H.-J., Bruckner, T., Tóth, F. L., & Hasselmann, K. (1999). The tolerable windows approach: Theoretical and methodological foundations. *Climatic Change*, *41*(3–4), 303–331.

Plummer, R. (2009). The adaptive co-management process: An initial synthesis of representative models and influential variables. *Ecology and Society*, *14*(2), Article No. 24.

Pretty, J. N., & Ward, H. (2001). Social capital and the environment. *World Development*, *29*, 209–227.

Putnam, R. D. (ed.). (2002). *Democracies in flux: The evolution of social capital in contemporary society*. New York: Oxford University Press.

Rackwitz, R. (2002). Optimization and risk acceptability based on the life quality index. *Structural Safety*, *24*(2), 297–331.

Raffensperger, C., & Tickner, J. (eds.). (1999). *Protecting public health and the environment: Implementing the precautionary principle*. Washington, DC: Island Press.

Reed, M. S., Evely, A. C., Cundill, G., Fazey, I., Glass, J., Laing, A.,. . . & Stringer, L. (2010). What is social learning? *Ecology and Society*, *15*, r1.

Renn, O. (2016). Inclusive resilience: A new approach to risk governance. In *IRGC 2016. Resource guide on resilience*. (pp. 184–191). Lausanne: EPFL International Risk Governance Center. v29-07-2016.

Rockström, J., Steffen, W., Noone, K., Persson, A., & Chapin, F. S. (2009). A safe operating space for humanity. *Nature*, *461*, 472–475.

Roman, P., & Thiry, G. (2016). The inclusive wealth index A Critical Appraisal. *Ecological Economics (Amsterdam)*, *124*, 185–192.

Rose, A. (2016). Measuring economic resilience to disasters: An overview. In *IRGC 2016. Resource guide on resilience*. (pp. 197–203). Lausanne: EPFL International Risk Governance Center. v29-07-2016.

Ryberg, M. W., Owsianiak, M., Richardson, K., & Hauschild, M. Z. (2016). Challenges in implementing a planetary boundaries based life-cycle impact assessment methodology. *Journal of Cleaner Production*, *139*, 450–459.

Sabatier, P. A., Focht, W., Lubell, M., Trachtenberg, Z., Vedlitz, A., & Matlock, M. (eds.). (2005). *Swimming upstream: Collaborative approaches to watershed management*. Cambridge, MA: MIT Press.

Savin-Baden, M. (2008). *Learning spaces. Creating opportunities for knowledge creation in academic life*. Maidenhead: SRHE & Open University Press.

Sayers, P., Hall, J., & Meadowcroft, I. (2002). Towards risk-based flood hazard management in the UK. *ICE Journal of Civil Engineering*, *150*(5), 36–42.

Scheffer, M. (2009). *Critical transitions in nature and society*. Princeton, NJ, USA: Princeton University Press.

Schneider, E., & Kay, J. K. (1994). Life as a manifestation of the second law of thermodynamics. *Mathematical and Computer Modelling*, *19*, 25–48.

Schneider, F., Kallis, G., & Martinez-Alier, J. (2010). Crisis or opportunity? Economic degrowth for social equity and ecological sustainability. Introduction to this special issue. *Journal of Cleaner Production*, *18*, 511–518.

Schultz, L., Folke, C., Österblom, H., & Olsson, P. (2015). Adaptive governance, ecosystem management, and natural capital. *PNAS*, *112*(24), 7369–7374.

Seager, T. P. [ISSST Network]. (2014). Dr. Thomas P. Seager - Resilient infrastructure requires new thinking. In IRGC (2016). *Resource guide on resilience*. Lausanne: EPFL International Risk Governance Center. v29-07-2016. Retrieved from http://youtu.be/OxDpLdCBbW4

Seager, T. P. [ISSST Network]. (2016). The failure of risk. In IRGC (2016). *Resource guide on resilience*. Lausanne: EPFL International Risk Governance Center. v29-07-2016. Retrieved from https://youtu.be/wYYoUTY9IA0

Sen, A. K. (1999). *Development as freedom*. Oxford: Oxford University Press.

Snell, M.L., Eisenberg, D.A., Seager, T.P., Clark, S.S., Oh, Y.J., Thomas, J.E., & McBurnett, L.R. (2016). A multidimensional review of resilience: resources, processes, and outcomes i. In *International risk governance council resource guide on resilience* (pp. 1–7).

Soares, C. G. Ed.. (2010). *Safety and reliability of industrial products, systems and structures*. London: Taylor & Francis, CRC Press. ISBN 0203818652, 9780203818657.

Solow, R. M. (1991, June 14). *Sustainability: An economist's perspective, paper presented at the Eighteenths J.* Massachusetts: Seeward Johnson Lecture to the Marine Policy Center, Woods Hole Oceanographic Institution, at Woods Hole.

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., ... & Folke, C. (2015). Planetary boundaries: Guiding human development on a changing planet. Science, *347*(6223), 1259855

Steffen, W., & Smith, S. M. (2013). Planetary boundaries, equity and global sustainability: Why wealthy countries could benefit from more equity. *Current Opinion in Environmental Sustainability*, *5*, 403–408.

Størseth, F., Tinmannsvik, R. K., & Øien, K. (2009, September 7–10). *Building safety by resilient organization – A casespecific approach*. Paper at the European Safety and Reliability Association Annual Conference (ESREL), Prague, Czech Republic.

Sundstrom, S. M., Angeler, D. G., Garmestani, A. S., Garcia, J.-H., & Allen, C. R. (2014). Transdisciplinary application of cross-scale resilience. *Nebraska cooperative fish & wildlife research unit – staff publications. 159*. Retrieved from http://digitalcommons.unl.edu/ncfwrustaff/159

Thorat, S., & Dubey, A. (2013). *How inclusive has growth been during 1993/94–2009/10? Part II: State-level analysis*. New Delhi, India: United Nations Development Programme.

Tierney, K. (1997). Impacts of recent disasters on businesses: The 1993 Midwest floods and the 1994 Northridge earthquake. In B. Jones (Ed.), *Economic consequences of earthquakes: Preparing for the unexpected*. (pp. 87–97), Buffalo, NY: National Center for Earthquake Engineering Research.

UNISDR. (2015a). Hyogo framework for action 2015–2030. Retrieved from https://www.unisdr.org/we/coordinate/hfa

UNISDR. (2015b). Disaster resilience scorecard for cities developed by IBM corporation and AECOM Retrieved from https://www.unisdr.org/campaign/resilientcities/assets/documents/privatepages/Resilience%20Scorecard%20V2.2%20-%20April%2030th%202015.pdf

van den Bergh, J. C. J. M. (2011). Environment versus growth — A criticism of "degrowth" and a plea for "a-growth". *Ecological Economics*, *70*(5), 881–890.

van den Bergh, J. C. J. M., & Kallis, G. (2012). Growth, a-growth or degrowth to stay within planetary boundaries? *Journal of Economic Issues*, *46*(4), 909–920.

Van Eck, N. J., & Waltman, L. (2014). Visualizing bibliometric networks. In Measuring scholarly impact (pp. 285–320). Springer, Cham

Vugrin, E. D., Baca, M. J., Mitchell, M. D., & Stamber, K. L. (2014). Evaluating the effect of resource constraints on resilience of bulk power system with an electric power restoration model. *International Journal of System of Systems Engineering*, *5*(1), 68–91.

Vugrin, E. D., Turnquist, M. A., & Brown, N. J. (2014). Optimal recovery sequencing for enhanced resilience and service restoration in transportation networks. IJCIS, *10*(3/4), 218–246.

Vugrin, E. D., Verzi, S. J., Finley, P. D., Turnquist, M. A., Griffin, A. R., Ricci, K. A, & Wyte-Lake, T. (2015). Modeling evacuation of a hospital without electric power. *Prehospital and Disaster Medicine*, *30*(3), 279–287.

Vugrin, E. D., Warren, D. E., & Ehlen, M. A. (2011). A resilience assessment framework for infrastructure and economic systems: quantitative and qualitative resilience analysis of petrochemical supply chains to a hurricane. *Process Safety Progress*, *30*(3), 280–290.

Walker, B., Holling, C. S., Carpenter, S. R., & Kinzig, A. (2004). Resilience, adaptability and transformability in social-ecological systems. *Ecology and Society*, *9*(2), 5.

Walker, B., & Salt, D. (2006). *Resilience thinking: Sustaining ecosystems and people in a changing world*. Washington, D. C., USA: Island Press.

Walker, B. H., Gunderson, L. H., Kinzig, A. P., Folke, C., Carpenter, S. R., & Schultz, L. (2006). A handful of heuristics and some propositions for understanding resilience in social-ecological systems. *Ecology and Society*, *11*(1), 13.

Walters, C. J. (1986). *Adaptive management of renewable resources*. New York: McGraw-Hill.

Waltman, L., & van Eck, N. J. (2013). A smart local moving algorithm for largescale modularity-based community detection. *European Physical Journal B*, *86*(11), 471.

Waltman, L., van Eck, N. J., & Noyons, E. (2010). A unified approach to mapping and clustering of bibliometric networks. *Journal of Infometrics*, *4*(4), 629–635.

Watts, D. J., & Strogatz, S. H. (1998). Collective dynamics of small-world networks. *Nature*, *393*(6684), 440–442.

WBGU (German Advisory Council on Global Change). (1995, March). Scenario for the derivation of global CO2 reduction targets and implementation strategies. *Statement on the occasion of the First Conference of the Parties to the Framework Convention on Climate Change in Berlin, Germany*.

WEF. (2015). Intelligent assets: Unlocking the circular economy potential. Retrieved from http://www3.weforum.org/docs/WEF_Intelligent_Assets_Unlocking_the_Cricular_Economy.pdf

White, M. (2003). Metaphor and economics: The case of growth. *English for Specific Purposes*, *22*, 131–151.

Wilkinson, R., & Pickett, K. (2009). *The spirit level: Why equality is better for everyone*. UK: Penguin.

Willis, H. H., & Loa, K. (2015). *Measuring the resilience of energy distribution systems, RR-883-DOE*. Santa Monica, CA: RAND Corporation.

Wondolleck, J. M., & Yaffee, S. L. (2000). Making collaboration work. *Conservation Biology in Practice*, *1*(1), 17–25.

Woods, D., Herrera, I., Branlat, M., & Woltjer, R. (2013). Identifying imbalances in a portfolio of safety metrics: the q4-balance framework for economy-safety tradeoffs. In Proceedings of the fifth resilience engineering symposium. (pp. 149–154). Netherlands: Soesterberg.

Yu, D. J., Rao, P. S. C., Klinkhaner, C. J., Krueger, E. H., Sangwan, N., & Sung, K. 2016. Aligning different schools of thought on resilience of complex systems and networks. In *IRGC. Resource Guide on Resilience*. Lausanne: EPFL International Risk Governance Center. v29-07-2016

Zevenbergen, C. (2007). *Adapting to change: Towards flood resilient cities*. Delft, The Netherlands: UNESCO-IHE. ISBN 978-90-73445-18-5.

Zevenbergen, C., van Herk, S., Rijke, J., Kabat, P., Bloemen, P., Ashley, R., & Veerbeek, W. (2013). Taming global flood disasters: Lessons learned from Dutch experience. *Natural Hazards*, *65*(3), 1217–1225.