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Review

Advancing Empirical Approaches to the Concept of Resilience: A Critical Examination of Panarchy, Ecological Information, and Statistical Evidence

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Abstract: Despite its ambiguities, the concept of resilience is of critical importance to researchers, practitioners, and policy-makers in dealing with dynamic socio-ecological systems. In this paper, we critically examine the three empirical approaches of (i) panarchy; (ii) ecological information-based network analysis; and (iii) statistical evidence of resilience to three criteria determined for achieving a comprehensive understanding and application of this concept. These criteria are the ability: (1) to reflect a system's adaptability to shocks; (2) to integrate social and environmental dimensions; and (3) to evaluate system-level trade-offs. Our findings show that none of the three currently applied approaches are strong in handling all three criteria. Panarchy is strong in the first two criteria but has difficulty with normative trade-offs. The ecological information-based approach is strongest in evaluating trade-offs but relies on common dimensions that lead to over-simplifications in integrating the social and environmental dimensions. Statistical evidence provides suggestions that are simplest and easiest to act upon but are generally weak in all three criteria. This analysis confirms the value of these approaches in specific instances but also the need for further research in advancing empirical approaches to the concept of resilience.

Keywords: resilience; panarchy; network analysis; information theory; diversity; redundancy; modularity

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1. Introduction

The concept of resilience is increasingly employed among researchers and policy-makers in different disciplines, especially in the emerging transdisciplinary field of sustainability science [1,2]. Despite its growing importance, the literature surrounding this concept is so copious and scattered that it is challenging for researchers to understand its ambiguities and the benefits of its application. On the one hand, the vagueness of resilience is argued to add to the creativity and transdisciplinarily nature of the concept [3], while on the other hand, it hinders consistent, meaningful application, and policy decision-making [4].

There is also a value judgment associated with the word resilience as a positive system quality; however, the specific context matters because a system may be resilient in a condition that would normally be viewed as negative—a poor community resilient to social change [5]; a rural farming village unable to attract health services; a bacteria resilient to antibiotics; financial lending inequalities; status quo gender or racial barriers, etc. In such cases, one must realize the 'duality of resilience' [6] and invest effort to break the system out of the resilient state toward a more socially desirable outcome.

The etymology of resilience can be traced to Latin, where *resilio* means "to jump back" [7]. Over centuries, the word has gone through various and at times contradictory meanings especially in psychology, engineering, sociology, environmentalism, and disaster management [8]. Numerous studies have attempted to shed light on the concept of resilience through various classifications and definitions [9–11]. A common emphasis of these studies is the critical need for empirical advancement on the concept of resilience [12].

This paper attempts a critical examination of the empirical advancements on the concept of resilience and specific to the themes of social ecology and sustainability. We aim to identify the principal contributions and major assumptions of the most significant approaches to the concept of resilience based on the following three criteria: (1) the ability to reflect a system's adaptability to shocks; (2) the ability to integrate social and environmental dimensions; and (3) the ability to evaluate system-level trade-offs. The paper is organized as follows. Section 2 discusses the three criteria put forward for this paper. Section 3 introduces our selection methodology and critically examines leading empirical approaches to resilience: (i) panarchy; (ii) ecological information-based network analysis; and (iii) statistical evidence. Section 4 provides a synthesis of the approaches and compares them using the three criteria. Section 5 concludes with suggestions for future research directions.

2. Criteria

2.1. Adaptability: Bouncing Back vs. Bouncing Forward

A useful categorization of resilience is to consider two overarching categories, engineering resilience and adaptive resilience [13]. In engineering resilience, the goal is to develop the capacity to withstand strain energy and maintain elasticity and resistance without breaking—i.e., returning to what is considered the original state [14]. In practice, this means that the design must consider an impossible, near fail-safe operation, in spite of unknown shocks and changing environmental conditions. A more realistic concept of resilience would also include the element of adaptability.

Consider various vital functions in our day-to-day lives such as electricity and water supply, waste disposal, emergency medical services, or policing. These functions prove the value of having a concrete normal state. In this context, therefore, resiliency is different from returning to what is perceived as normal and instead indicates an adaptive capacity to reorganize into a different operating structure while maintaining function [15]. The resilience of the system with modified structure raises new questions: which parts can be permitted to fail and which parts are critical and must remain intact? What training and preparation are needed to be able to cope with unexpected shocks? In this vein, improvisation, learning, and emergent leadership become critical [16]. Without adaptability, such questions become irrelevant as a system, including all of its subsystems, that is unable to return to normal conditions when faced with a stress fails to survive and function. With adaptability in mind, it is necessary to consider the questions "resilience of what?" and "resilience to what?" [17].

Adaptive resilience allows for a system to maintain distinct configurations. In ecological studies this is known as multiple attractors, where an ecosystem can switch from one resilient configuration to another, each of which maintains a distinct ecological equilibrium. The existence of multiple attractors is not limited to ecosystems and can be related to all systems. To identify the various attractors of a system is a challenging task. Firstly, the records of the system's behavior might be unavailable. Secondly, a certain system can simply be too complex to identify its various attractors or even evolve into new attractors. Thirdly, the magnitude and nature of the stress to a system may also be unique and without precedence. Therefore, while a system's configuration may be resilient, it may be impossible to predict the adaptive characteristics before it encounters the shock. This may be discouraging for planning purposes but still provides guidance to anticipate the types of emerging responses and possibilities.

2.2. Avoiding Centrism: Integrating Social and Environmental Dimensions

There is a strong mutual interdependence between social and environmental systems (SESs) [15,18]. Empirical approaches to the concept of resilience therefore need to be evaluated for their success in handling such integrated systems. Empirical approaches that only consider the resilience of either the environmental (eco-centric) or social (anthropo-centric) dimensions on their own are inadequate in their ability to grasp reality or be useful to practitioners. This reality encompasses the interaction of humans and their society and the effects of their decision-making and policy on the environment.

Achieving an integrated understanding of both social and environmental dimensions is not easy. One approach that researchers have forwarded is the use of network flows as socio-environmental proxies. The roots of these approaches lie in systems ecology [19,20], a field in which thermodynamic analytics, e.g., emergy and exergy currencies, simplified the multidimensionality of the socio-economic and environmental dimensions into units of common denominators, e.g., joules, nats, and solar emjoules. However, this raises a basic dilemma of how to express quantities of a system through common denominators while fully reflecting the heterogeneities of the system. Specifically, the challenge in the integration of socio-environmental dimensions is 'where' and 'how' to integrate different values. Regarding the how, theoretical approaches mainly include accounting approaches such as emergy, exergy, and the ecological footprint [21]. Regarding the where, researchers have forwarded integration of dimensions at different spatial granularities [22,23].

The implications of feedback between social and environmental dimensions also need to be addressed by empirical approaches. This entails two points: firstly, implications of feedback from the social to the environmental, e.g., how decision-making puts pressure on the availability of resources; secondly, implications of feedback from the environmental to the social dimension, e.g., how environmental changes influence human decision-making and consumption behavior. Researchers have gained significant insight into the former rather than the latter. Specifically, models have examined species resilience under anthropogenic pressures and their conservation implications. In these models, environmental regime shifts are observed by anthropogenic resource consumption, e.g., rate of phosphorus use [24] and intensive variables such as cycling [25–27]. While these models have decision-making potential on optimal managerial problems, e.g., decisions relevant to resource harvesting vs. regenerating strategies, they do not fully capture the feedback of changing environmental dynamics on human decision-making and management. Specifically, the response and adaptability of decisions [28,29] to environmental feedback needs to be better reflected. More recent models attempt to address adaptive human behavior to environmental change using agent-based approaches to represent social changes [30–33].

2.3. Practicing Resilience: The Ability to Evaluate System-Level Trade-Offs

Given the complexity of social environmental networks and the feedback that defines their interrelationship, empirical approaches to resilience are useful firstly as practical tools that present trade-offs in decision-making. Secondly, at a more advanced level, empirical approaches to resilience are most useful if a normative criterion would govern such trade-offs and be relevant to stakeholder applications. The literature surrounding the concept of resilience that presents such trade-offs can be categorized into either temporal or spatial trade-offs.

The notion of resilience as the inverse return time is most suitable to resilience-based simulations where researchers are interested in the time required for a system to return to an original or equilibrium state following a disturbance [34,35] or to reach a certain level of "abundance" [36]. However, this raises the concern that resilience is not simply returning to a previous state and maintains elements of adaptability [37]. In this vein, Holling [37] proposed an evolutionary worldview whereby systems that are unstable in the short term may still in fact be resilient in the long term. This evolutionary worldview has important implications for decision-making, specifically where short-term, fast-moving variables are considered to be in a trade-off with long-term slow-moving variables. This is best illustrated in ecosystem service management studies, highlighting the conflicting objectives of increasing short-term profit from resource consumption with the long-term ability of the ecosystem to regenerate itself.

The second category within the literature surrounding the concept of resilience has focused on spatial distinctions. These discussions emphasize a causal link between how a networked system is configured spatially and the network's ability to withstand shocks and disturbances. In social network research, it has been revealed that scale-free networks are resilient to random disturbance while those less resilient to disturbances are targeted to highly connected hubs [38–40]. This discovery is significant as many human-made networks are scale-free, e.g., communication networks, electricity grids, and financial networks. However, research in this stream has been dominated by simplified networks, i.e., as undirected and un-weighted flows, and therefore not fully reflective of the complexities of socio-environmental networks. Furthermore, the description of a topology of a network as scale-free, random, or exponential is difficult to translate into reality and made relevant to the stakeholder application of managing resilience. More relevant to the stakeholder application are spatial distinctions that can be modified and managed as system trade-offs in priorities.

3. Empirical Approaches to Resilience

3.1. Selection Methodology

A series of online searches was conducted to identify the top peer-reviewed journals focusing on interdisciplinary research on human and environmental interactions and challenges. Using the SCImago Journal & Country Rank (SJR) portal, we examined all journals under the subject area of "environmental science" and subject categories of "environmental science (miscellaneous)" and "renewable energy, sustainability, and the environment". From these results we excluded journals that were not interdisciplinary in their scope and then selected the remaining top 30 journals according to the (SJR) rank indicator tool. These rankings are archived under the June 2015 dataset in the Journal Metrics website [41]. The names and rankings of the selected journals are shown in Table 1.

Table 1. Top 30 journals by SJR rank (2014) reviewed in this paper.

Number	Journal Title	SJR Rank
1	Frontiers in Ecology and the Environment	4.054
2	Global Environmental Change	3.006
3	Annual Review of Environment and Resources	3
4	Review of Environmental Economics and Policy	2.752
5	Journal of Environmental Economics and Management	2.636
6	Environmental Science and Technology	2.464
7	Environmental International	2.38
8	Environmental Research Letters	1.87
9	Ecosystems	1.825
10	Ecological Economics	1.616
11	Environmental Science and Policy	1.607
12	Journal of Cleaner Production	1.588
13	Environmental Research	1.574
14	Global and Planetary Change	1.572
15	Current Opinion in Environmental Sustainability	1.544
16	Journal of Industrial Ecology	1.531
17	Ecology and Society	1.455
18	Environmental Innovation and Societal Transitions	1.438
19	Science of the Total Environment	1.437
20	Sustainability Science	1.348
21	Ecological Indicators	1.267
22	Ecological Engineering	1.121
23	Ecological Modelling	1.066
24	Journal of Environmental Informatics	1.042
25	Organization and Environment	1.036
26	Journal of Environmental Sciences	0.799
27	Ecological Complexity	0.778
28	Environmental Management	0.773
29	Ecological Informatics	0.658
30	Sustainability	0.452

To identify existing literature within these journals dealing specifically with empirical approaches to resilience, we visited the web portal of each journal and searched for the term "resilience" and also the related term "robustness" from the year 1980 to 2015 within the title, abstract, and keywords. The resulting journal papers were then individually scrutinized for developing or employing unique and widely cited empirical approaches to the concept resilience. Following the above methodology, our search resulted in identifying the approaches of (i) panarchy; (ii) ecological information-based network analysis, and all others categorized into a group termed (iii) statistical evidence. To provide a comprehensive review of the above approaches, we used Google Scholar to find highly-cited sources relevant to each approach—this search was not restricted to our list of selected journals.

3.2. The Panarchy Approach

The panarchy approach has chiefly been used descriptively in case studies and there have been few advances in using the approach as an analytical or predictive tool. However, while the theory has not been quantitatively tested, there have been some important contributions in this avenue [26,42,43]. A central assumption of the approach is that socio-ecological systems are not obliged to remain within a certain basin of attraction and following a disturbance can adapt to new circumstances by reorganizing and establishing new novel trajectories. The panarchy approach has been utilized in various research fields, including forests [44], water systems [45–48], rangelands [25,49,50], agricultural regions [51], fisheries [52], aboriginal cultures [53], and archaeological cases [54].

The simplified panarchy approach illustrates a two-dimensional adaptive cycle plotted against two axes [44,46,55]. (1) The degree of system capacity Y-axis describes the system's 'potential for change', i.e., its ability to adapt based on alternative future options. The system increases its potential by accumulating wealth through novelties that generate returns and following a disturbance depletes its potential to reorganize and adapt to the new circumstances; and (2) the degree of system institutionalization X-axis describes the connectedness among the system's variables and processes and reflects the flexibility or rigidity of the system.

Against the above axis, the panarchy approach depicts a cyclic pattern, inspired by the infinity symbol (see [56] for a modified depiction), which is divided into four phases, i.e., exploitation (r), conservation (K), release (Ω), and reorganization (α). Moving from (r) phases, systems are described as exploiting resources using this surplus to increase their internal organization. Moving from (r) to (K), the system increases its institutionalization, but with decreasing potential for new novelties. The overall system resilience is assumed to decrease during this phase. In the (K) phase, the system accumulates and conserves capital, e.g., plant structure or financial capital, and increasingly becomes more rigid and brittle. In this phase, while the system aims to maximize its institutionalization, it does so at the cost of decreasing its resilience to disruptions. For example, disruptions may include forest fires, outbreaks of disease, and earthquakes. Once the system experiences such a disruption, it enters the (Ω) phase, which is described as a period of collapse and simplification. This phase can be viewed as a period of creative destruction whereby previously accumulated capital is released. Using its potential the system enters the (α) phase, where through reorganization the system leads to the rise of novelties (e.g., genetic mutations or business innovations). Following the (α) phase and re-entry into (r) phases, the system may have adapted to a different set of processes, structures, or basins of attractions. The approach has been modified and applied to management of social systems in [16], as expressed in Figure 1.

The panarchy approach describes the resilience of the system as increasing and decreasing through the cycle. The increase of resilience is argued to be necessary for the system to adapt to new circumstances through novelty following a shock. Specifically, in the (α) phase the system is described to maintain low connectedness, necessary for rearranging previously rigid structures, and high resilience, necessary for testing such new re-arrangements. On the reverse side, in the conservation (K) phase, the system minimizes resilience while maximizing rigidity in exploiting resources. The dynamics of the panarchy approach, as illustrated in Figure 1, also indicate two extreme cases of poverty and rigidity traps. A poverty trap occurs when the system exhibits low resilience, connectedness, and potential—for example, a savanna that through human over-exploitation enters into an irreversible and pernicious cycle of further erosion and economic disincentive for sheep grazing [55]. On the other extreme, a rigidity trap occurs when the systems exhibit high resilience, connectedness, and potential. For example, social caste systems or rich yet unproductive developing countries are afflicted with what is called the 'oil disease'.

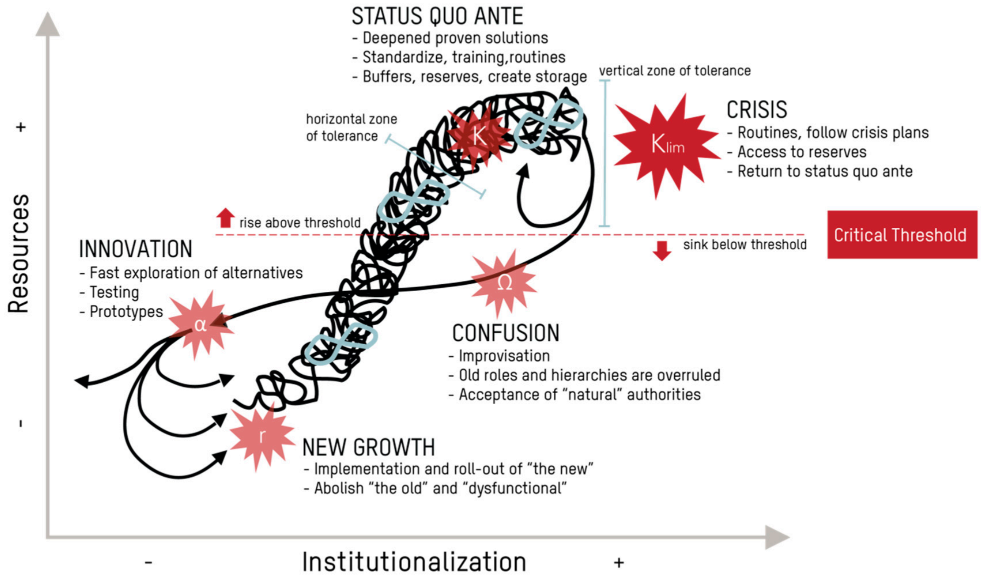

Figure 1. Adaptive cycle applied to social systems. Stages in this cycle are similar to ecological stages, from new growth to status quo, to confusion, and innovation. The differentiation between crises that remain within the threshold and those that lead to dissolution are indicated by the vertical range of tolerance.

3.3. Ecological Information-Based Network Approach

The ecological information-based network approach examines configurations of flows within a network of interactions. The central assumption is the notion that the system resilience depends largely on the topology and magnitudes of the pathways by which energy, information, and materials are circulated [57]. In this vein, the ecological information-based network approach identifies system-level trade-offs between the efficiency and redundancy of flows within a system and identifies the resilience of the system as a balance between these two variables.

This approach has been applied to natural resource management [58,59], economic systems [60], virtual water networks [61], socio-ecological systems [62], sustainable development [63], food-webs [64,65], river basins [66], urban ecology [67], irrigation management [68], and marine ecosystems [69].

The approach is rooted in the Boltzmann Index, where total system indeterminacy H, represents the total potential of a system to evolve or to self-organize. H can be decomposed into two variables such that $H = X + \psi$ [70]. Here, ψ is the remaining uncertainty of a network after the flows T_{ij} are observed and X represents the amount of uncertainty that is resolved by observing the connection among flows. For a networked system, the above variables are defined by [71]:

$$H = -k \sum_{i,j} \frac{T_{ij}}{T_{..}} log \frac{T_{ij}}{T_{..}} \tag{1}$$

$$X = k \sum_{i,j} \frac{T_{ij}}{T_{..}} log \frac{T_{ij} T_{..}}{T_{i.} T_{.j}} \tag{2}$$

$$\psi = -k \sum_{i,j} \frac{T_{ij}}{T_{..}} log \frac{T_{ij}^2}{T_{i.} T_{.j}}. \quad (3)$$

Here, T_{ij} is the flow from node i to node j, $T_{i.} = \sum_j T_{ij}$ is the total flow leaving node i, $T_{.j} = \sum_i T_{ij}$ is the total amount of medium entering node j and the sum of all flows in the system, $T_{..} = \sum_{ij} T_{ij}$, is known as the "total system throughput" (TST).

In information theory, variable X, known as the "average mutual information" (AMI), is the difference between the uncertainty of the destination of the flow leaving node i and the uncertainty that remains after the flow from node i to node j is observed. This can be interpreted as the efficiency of the network, or, more precisely, the measure of the average degrees of constraint in the network for all flows T_{ij}. Variable ψ, known as the conditional entropy, is the measure of the average degrees of freedom in the network for all flows T_{ij}. Given the degree of constraints of a flow leaving node i, ψ can be interpreted as the redundancy of the network, or, more precisely, the remaining choice of pathways for flows going to node j. Both of these metrics, ψ and X, are dimensionless and based on units of information depending on the base logarithm used in their calculation, e.g., *bits* if the base 2 logarithm is used or *nats* if the natural logarithm is used.

Intuitively, following a disruption, networks with more diverse connections are more flexible in rerouting their flows and maintaining critical functions. Conversely, a more efficient network with a minimal number of well-organized connections can concentrate its capacity for growth and development. As illustrated in Figure 2, overly redundant networks may be incoherent and lacking the efficiency to grow, while overly efficient networks may be brittle and prone to collapse when subjected to stress. To help determine a balance between the constraint imposed by efficiency and the flexibility provided by redundancy, the relative order in the system is introduced as:

$$\alpha = Efficiency/\ (Efficiency + Redundancy)$$

where $0 \leq \alpha \leq 1$. While keeping in mind that order results from the opposing and dialectical tendency of efficiency and redundancy within the system, the ratio α is a convenient way to express the degree to which order dominates the system. Taking the measure of relative order and again invoking the Boltzmann measure of its disorder, which is given by the negative log of α [72], system robustness can be expressed as [73]:

$$Robustness = -\alpha \log(\alpha)$$

Recalling that $ln\,(1) = 0$, it is evident that as the system progresses towards either extreme, i.e., too little efficiency or too little redundancy, the robustness of the system, in terms of this trade-off, approaches zero. The optimal level of robustness for a system can depend on the environment, stage of development, levels of stresses, and the mechanism forming the network. This quantitative measure of robustness is one key property of a resilient system.

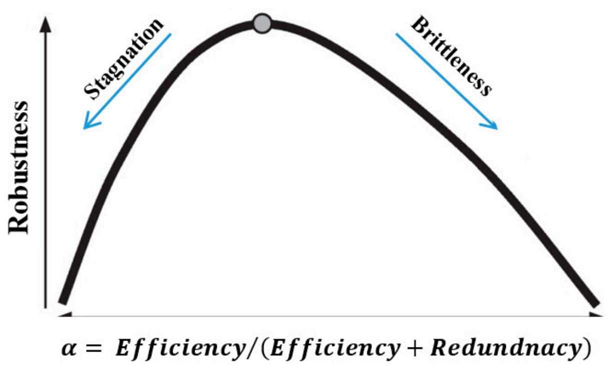

Figure 2. Conceptual model of the ecological information-based approach.

3.4. Statistical Evidence of Resilience

The concept of resilience is not a visible feature and at best is a concept reflecting the response of a system to probable or at times improbable future events. In the absence of reliable data, knowledge of complex non-linear dynamics, and uncertain future shocks, the management of resilience is best achieved through statistical correlations. System properties correlated with resiliency have been identified across a range of social science, environmental, and economic disciplines. The most common of these system properties include modularity and redundancy/diversity [11,74,75]. Presumably, tuning the system according to these properties invests in the ability to withstand a shock or disturbance, reduce risks, and improve recovery. Modularity can be related to the degree of the connectivity of a system, whereas redundancy (also measured as diversity) relates to the variety among elements of the system. These properties, their overlaps, and trade-offs are research frontiers in socio-ecological systems.

3.4.1. Modularity

Modularity is a system property measuring the degree to which densely connected nodes within a network can be decoupled into separate communities or clusters that interact more among themselves than nodes in other communities. In a system with strong interconnections among components and little modularity, a disturbance to one component may travel quickly to other components and result in the collapse of the system. By contrast, systems with high modularity are better able to 'contain' a shock within a module without damaging other components. For example, consider how firebreaks in forest land management may impede the spread of fire or how airport quarantines may prevent the spread of epidemics or invasive plants. Modularity has increasingly been identified in different disciplines as an important attribute for resilience, i.e., in ecology and food-webs [75–77], in network science [78,79], in finance and economics [80–82], and in socio-ecological research [74,83,84].

Among the various disciplines, ecologists and food-web modelers have carried the most pioneering research on modularity. Recent empirical work conducted on food-webs has confirmed that food webs are more compartmentalized than a null model where species interact with equal probability with other species [76,77,85]. Despite growing research in the ecological field, modularity remains an under-researched topic in other disciplines. For example, trade-offs between modularity and other system-level properties [86], especially for socio-ecological systems, is an important research frontier.

Many methods are described in the literature for evaluating and measuring modularity; despite the challenges of a precise mathematical definition [87], modularity maximization is the most widely used and accurate method [88–90]. In this approach, the modularity of a network partition is evaluated by comparing its number of links against a null network model, i.e., equal number of nodes, links, and degree distribution but with random links among the nodes. From the above definition, a modularity function is defined that can measure the quality of the introduced partitions (P) as a community:

$$P = \frac{1}{T_{..}} \sum_{ij} \left[T_{ij} - \frac{T_{i.} T_{.j}}{T_{..}} \right] \delta_{c_i c_j}$$

The expected fraction of links is measured with the assumption that the probability that nodes i and j are connected is $\frac{T_{i.} T_{.j}}{T_{..}}$. Here, $T_{i.}$ and $T_{.j}$ are, respectively, the output and input strengths of nodes i and j, $T_{..}$ is total strengths of the network, and δ is Kronecker's delta where $\delta_{c_i c_j} = 1$ if nodes i and j are in the same community and $\delta_{c_i c_j} = 0$ if otherwise. In any given network, there are numerous possible partitions and therefore communities can be evaluated by finding the best fit for modular partitions. This can be achieved using heuristic algorithms, e.g., spectral algorithms [91] and Tabu search algorithm [92].

3.4.2. Redundancy/Diversity

Diversity is an important concept with applications in various disciplines. Diversity can be defined as the degree of variation. This may include functional diversity, i.e., the degree of the variations of components which maintain similar functions, or response diversity, i.e., the degree of the variations of components which exhibit different responses resulting from disruptions [93]. Systems maintaining such diversities can in principle be more flexible when faced with a disruption or shock. For ecologists, diversity is seen as an essential component for ensuring flexibility and a long-term survival strategy for natural ecosystems. Recently, diversity has been acknowledged to be similarly important for socioeconomic systems as well [94,95].

Diversity has been argued as encompassing three properties, i.e., variety, balance, and disparity [96,97]. Variety is in reference to the categorical types that are available—for example, the number of types of species, resources, or products available. Balance is in reference to the apportionment of elements across available categories, i.e., the more even the distribution, the greater the diversity. Disparity is in reference to the degree to which the categories themselves can be differentiated from one another. For example, in reference to energy diversity, solar-photovoltaic and solar-thermal are more closely related than wind and gas energy. While there is no mathematical representation that considers all three of these properties of diversity, the Shannon–Weaver index is the preferred approach because it takes into consideration both variety and balance [97]. The Shannon–Weaver index [98,99] is defined as:

$$H = -\sum_{i} p_i ln\,(p_i) \tag{4}$$

Here p_i represents the share of category i in the total mix of categories. The higher the value of H, the more diverse a system is evaluated to be. The Shannon-Weaver index has been applied for evaluating ecosystem resilience by ecologists [19] and, more recently, for evaluating the distribution of energy systems in economic systems [95,96,100].

4. Synthesis

Despite its inherent ambiguities and evasiveness, the concept of resilience continues to be a priority for researchers, policy makers, and practitioners. In this paper, the principal contributions and major assumptions of the empirical approaches of resilience are evaluated based on three criteria: (1) their ability to reflect a system's adaptability to shocks, i.e., bouncing back vs. bouncing forward; (2) their ability to integrate social and environmental dimensions; and (3) their ability to evaluate system level trade-offs. In this section, we compare the approaches discussed in the previous sections using these criteria and identify the strengths, weaknesses, and potential areas of improvements for future research. A summary of our findings is presented in Table 2.

Table 2. Summary of comparison of the three empirical approaches to resilience against the three criteria of adaptability, integration of social and environmental dimensions, trade-offs, and future research directions.

Criteria	Panarchy	Ecological Information-Based	Statistical Evidence
Adaptability: Bouncing back vs. bouncing forward	Responsive; flexible in considering adaptation scenarios	Potentially responsive; requires intensive data on historical basins of attraction	Weak in considering adaptation
Avoiding Centrism: Integrating Social and Environmental Dimensions	Effective in reflecting social feedback	Weak; requires the use of a common denominator which leads to centrism	Weak; requires the use of a common denominator which leads to centrism
Practicing Resilience: The ability to evaluate system level trade-offs	Presents descriptive trade-offs, however no normative criteria is presented and trade-offs are difficult to quantify	Applicable trade-off presented between efficiency and redundancy of flows, however a general normative criteria, although feasible, is not available	No trade-off presented, however versatile in application
Future Research	Quantifiable measurements of variables and reflection of environmental feedback	Data-intensive case studies with a focus on identifying basins of attraction for better reflection of adaptability	Trade-offs and overlaps of statistical evidence of resilience.

4.1. Adaptability: Bouncing Back vs. Bouncing Forward

Following a shock, a system can be deemed resilient if it either returns to its original state of equilibrium or adapts to a new equilibrium. In most social and environmental systems, adaptation to new conditions resulting from a shock is a critical requirement and therefore empirical approaches to resilience need to reflect this feature. Among the approaches examined in the previous sections, panarchy and the ecological information-based approaches are reflective of this property. Panarchy rests on the foundation that systems deal with unpredictable change by utilizing cross-scale and adaptive system features. Specifically, the panarchy approach is very flexible in its multi-dimensionality, it being a very "grounded theory" where the axes are subjective to allow the end-user to devise his/her own adaptive scenario worldviews. Therefore, most case studies employing this approach describe different socio-ecological scenarios that the system can effectively "bounce forward" following a disruption. For example, in the rangeland model examined by [25], a "high shoot biomass" and a "null shoot biomass" equilibrium is described as two scenarios to which the system can adapt.

Using the ecological information-based network analysis to evaluate resilience based on probabilistic responses of a network to a disturbance relies on the construction of a flow network based on available data. Unlike panarchy, this approach is data-intensive and does not provide the subjectivity for end users to devise adaptive scenarios. However, given adequate time-series data, ecological information is effective in mapping different basins of attractions based on the history of the system [101]. This resilience landscape can reflect the adaptability of the system to different environmental conditions. Similarly, the weakness of the statistical evidence approach in considering adaptation can be greatly improved by a data-intensive mapping of possible basins of attraction.

4.2. Avoiding Centrism: Integrating Social and Environmental Dimensions

It is critical for empirical approaches of resilience to avoid centrism and integrate both the social and environmental dimensions of a system. This requires a reflection on both social and environmental feedback and their effects on one another. The approaches examined in the previous section are all weak on this criterion. However, panarchy may be the most effective in capturing social feedback. Specifically, the subjective versatility of the panarchy approach has been used in many case studies [30,102,103] to examine the effect of social and economic decisions in the system. This is crucial in the management of natural resources; however, more research is needed to advance this approach in consideration of environmental feedbacks upon social dimensions. The chief challenge with the ecological information and statistical evidence of resilience lies in their usage of flows in their analysis. While social and environmental flows in a system are measured in various units, these approaches require their representation in a common denominator. The accounting of flows inherently entails a centric approach whereby the choice of denominator effectively weakens the integration of the two dimensions.

4.3. Practicing Resilience: The Ability to Evaluate System-Level Trade-Offs

The challenge of interpreting trade-offs between system-level properties relevant to the resilience of socio-ecological systems is of great significance to practitioners. The reviewed approaches have varying degrees of success on this criterion. By distinguishing scenarios based on evolutionary phases of a system, panarchy succeeds in identifying different system trade-offs. This entails distinguishing good attractors from bad attractors according to the desired state of the system. For example, in a rangeland model [25], a trade-off is identified as conflicting objectives of increasing short-term profit while preserving the long-term sustainability of the rangeland. Increasing the stocking rate (animals/ha) of the rangeland increases short-term gain, but can lead to effectively irreversible degradation of the rangeland if the resultant grazing pressure is too high. Alternatively, keeping the stocking rate too low can lead to substantial loss of income. While panarchy succeeds in presenting to the stakeholder trade-offs relevant to managing the resilience of the system, it does not offer normative criteria to determine the level of suitable or optimal management. Furthermore, panarchy has not significantly advanced from a descriptive model to a quantifiable approach and therefore the measurement and degree of progress on the various trade-offs are difficult to monitor.

The ecological information-based network approach successfully identifies and quantifies the trade-offs of efficiency and redundancy relevant to the resilience of a system. However, this approach does not offer any normative criteria as a balance between these two parameters. In this vein, researchers have suggested biomimicry or historical data as one possible normative criteria [57]. Further research is warranted in proposing and evaluating normative criteria relevant to various systems. Specifically, researchers need to address how to effectively modify these system-level properties [104] and how to address the challenges of flow data availability.

The relationships between statistical evidence of resilience, i.e., diversity and modularity, offer no particular trade-off and simply prescribe higher levels of each property. Despite their weaknesses, statistical approaches are highly versatile in their application to an expected disturbance. For example, practitioners can apply diversity and/or modularity to available inflows, outflows, and metabolic pathways within a system. Practitioners can also increase the modularity and/or diversity of system responses to a shock. Therefore, despite the shortcomings of the statistical approach in evaluating system trade-offs, the application of diversity and modularity are highly transparent and versatile.

5. Conclusions

In this paper, we critically evaluate the three empirical approaches to resilience, i.e., panarchy, ecological information-based network analysis, and statistical evidence, against three criteria. These criteria include: (1) the ability to consider adaptation; (2) the ability to integrate both social environmental dimensions; and (3) the ability to evaluate system level trade-offs. Our findings can be used to better position the strengths, weaknesses, and relevance of these empirical approaches to the concept of resilience.

It is important to recognize that systems simultaneously express multiple characteristics that are critical to their long-term resilience. Therefore, a portfolio approach may provide a plurality of approaches and when applied to actual case studies, the reality of the specific place resolves some of the academic incongruities. Space dissolves the "either-or" thinking that may be possible in the abstract. We are confronted with decision-making at the scale of the problem and what works best at that specific space-time expression becomes apparent. It is evident that any system contains a diversity of actors functioning in different stages: some are recovering from disturbance, others are growing, others are sustaining equilibriums, and yet others are experiencing collapse. There is no one lock-step synchronicity to which system behavior corresponds. This diversity of experience provides roles for diverse actors and also resilience for the overall system. In other words, the system exhibits patchiness in function. Therefore, making generalizations as well as finding a one-size assessment metric is difficult. Ecosystems are model systems in terms of expressing patchiness, yet for efficiency reasons are often omitted from the design of social systems. In ecology, meta-population theory has been used to model the movement of populations within a patchy landscape, but these approaches have not been fully explored in other social-environmental contexts. This recognition of the role of patchiness sheds some light on the challenges of applying empirical-based resilience measures.

For advancing these approaches, we suggest the following research avenues. More research should be centered on developing quantifiable measurements for reflecting environmental feedbacks in the panarchy model. The ecological information-based network analysis, while promising in its application, is data-intensive in nature and for future research we suggest more research examining various basins of attractions of a system case study. Research in this avenue will progress the ecological information-based approach to better reflect adaptability. The statistical evidence on resilience, especially in the absence of complete information of the system, is a promising avenue for the application and management of resilience. However, the trade-offs and overlaps of these properties are not examined and future research along this avenue should be focused on advancing this area. The concept of resilience is complex and progress in our understanding also requires more effort in cross-referencing and experimenting among the three empirical approaches.

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