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Redundancy, Diversity, and Modularity in Network Resilience: Applications for International Trade and Implications for Public Policy

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ABSTRACT

Sustainability is increasingly concerned with the complex interactions between nature and society, and we need to seek solutions towards the challenges that threaten humanity's collective wellbeing. Towards this end, it is critical to advance the application of research examining the dynamic interactions of the components of complex social-ecological systems and their emerging properties. A key research area is on advancing tools and strategies relevant to the evaluation and strengthening of resilience. Redundancy, diversity, and modularity are important characteristics of resilience with a high potential for application in various critical social-ecological systems. This paper provides a critical overview of the theoretical underpinnings of modularity and redundancy and their application in measuring resilience of trade networks with implications for public policy and institutional design.

1. Introduction

The concept of resilience is widely adopted in policy, decision making, and research focusing on challenges of sustainability and sustainable development. Sustainable development, as an anthropocentric approach that informs decision-makers and individuals how to meet basic needs and maintain intergenerational equity, is a normative concept encompassing integrated social, economic and environmental concerns,; the concept of resilience is descriptive in its nature and reflects system dynamic properties that are relevant in assessing sustainable development targets. While these two concepts may be complementary, they are vastly independent concepts. The importance of the concept of resilience continues to grow in the rhetoric surrounding sustainable development. This is perhaps best reflected in the Sustainable Development Goals (SDG) agenda, where the concept of resilience is frequently used in the agenda's goals, targets, and indicators: on Poverty: target 1.5; Hunger: target 2.4; Industry, Innovation, and Infrastructure: targets 9.1 and 9.A; Sustainable Cities and Communities: targets 11.B and 11.C; Climate Action: targets 13.1; and, Life Below Water: target 14.2. Many systems critical to humankind's sustainable development are prone to shocks and disturbances. Additionally, many of these systems such as water, energy, food, and trade exhibit inherent interconnectedness. For example, food trade between countries indirectly relies on water resource availability for agriculture within exporting countries. When one such a system comes under shock or stress, its interconnections can lead to cascading failures in other connecting and co-dependent systems. Therefore, resilience of social-ecological systems is increasingly a critical concept in our daily lives; especially as humanity is now more connected than ever, we often see that the world as less resilient to shocks and disruptions. The recent spread of the zoonotic disease covid-19 from animals to humans, from one country to another, and the resulting cascading socio-economic impacts on the global economy serves as an example of our interconnectedness and fragility.

While the interconnectedness and complexity of our social-ecological systems have increased considerably, our understanding of the dynamic behavior of these systems has not kept pace. At the aggregate level, these systems may exhibit unpredictable behavior and risk our capacity for

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sustainable development by exacerbating our vulnerability to financial shocks, political instability, diseases, and climatic impacts. Given the complexity of social-ecological systems, researchers have difficulty in explaining or predicting their collapse and their long-term effects. A network approach that considers the direct and indirect transactions and relations between nodes is one method that quantitatively includes cascading influences. These concerns have led to an increasing interest in situating the concepts of resilience and interdisciplinary network approaches to challenges of, for example, economic growth (Battiston et al., 2016; Maluck & Donner, 2015). The evolutionary history of natural systems (May et al., 2008) indicates that new approaches arising from our understanding of ecological networks and their structural properties of redundancy, diversity, and modularity (Levin & Lo, 2015) can be useful in this avenue.

Redundancy is exhibited as the diversity of pathways (i.e., the multiplicity of pathways) and is critical for a system's capacity to adapt under changing environmental conditions arising from shocks and disturbances (Kharrazi et al., 2016). For example, in a complex trade system, resilience to shocks can be achieved by choosing from different agents and therefore maneuvering towards more robust suppliers. Modularity, on the other hand, is a system property that measures the degree to which a network's densely connected nodes can be decoupled into separate communities or clusters (Levin, 1999). The configuration of systems are heavily influenced by the type and degree of positive feedbacks at play that can draw increasing amounts of matter or energy into the orbit of the participating members, a process referred to as centripetality (Ulanowicz et al. 2006) For example, economic trade blocs or modular electricity grids can have high modularity and therefore interact more amongst themselves than nodes in other communities. In systems with low modularity, a disturbance to one component may cascade quickly to other components and lead to the collapse of the entire or large portion of the system. In contrast, the ability of highly modular systems to 'restrain' or 'buffer' a shock without allowing its spread to the global network is beneficial property.

This discussion paper provides a critical overview of the theoretical underpinnings of modularity, redundancy, and diversity as network metrics of resilience and their application to resource trade networks. It can be anticipated that the elucidated approaches in this paper may apply to other networks and inspire the development of additional empirical research focusing on resilience in a broad range of disciplines. This paper is organized as follows: Section 2 discusses the theoretical definitions of diversity, redundancy, and modularity. Section 3, overviews the application of these system properties to critical social-ecological systems. Section 4 provides a discussion on resilience as a public good. Finally, a conclusion and discussion on future research avenues follow in Section 5. It is hoped that the discussions in this paper inspire new advances in translating structural properties of networks into explicit applications towards the resilience of social-ecological systems critical to humanity's sustainable development.

2. Statistical Characteristics of Resilience: Modularity, Redundancy, and Diversity

The resilience of a system is not easily discernable, as 'resilience' would reflect a range of responses to probable or often unforeseen future shock events and stresses. The interplay between the system itself and the type of shock also affects a network's resilience response; thus, requiring a reflective or recursive approach. A system that is resilient to random shocks may perform poorly to targeted attacks, a behavior common in scale-free networks where network flow is concentrated on a handful of nodes (Barabási & Bonabeau, 2003). Furthermore, many social-ecological systems lack comprehensive temporal and spatial data which accentuate our incapacity to predict their complex non-linear dynamics. Given these fundamental uncertainties, the management of the resilience of complex social-ecological systems is best achieved through the identification of network metrics within resilient systems. The most common statistical correlations with the resiliency of social-ecological systems identified in the literature are modularity, redundancy, and diversity (Biggs et al., 2015; Levin, 1999; Martin-Breen & Anderies, 2011). By increasing the strength of these properties, systems may better withstand and recover from shocks and stresses. Modularity is a measurement of the strength of dividing a system into groups of communities and is related to the degree of connectivity within a system. As seen from Fig. 1, increased modularity in a network safeguards the network against the spread of shocks such as infectious diseases. Alternatively, increased modularity in, for example, food supply chains can also result in access to food being cut-off during local food scarcity. Diversity and redundancy, on the other hand, relate to the variety of elements, e.g., components, functions, and pathways, in a system. Fig. 1 also explains the benefit of redundancy and modularity in pathways for network resilience. Each circle represents nodes in the system with multiple links representing pathways between nodes A to B. Diversity is also represented in this figure, where more than one node of each color/type in the network is available. For example, it is the diversity of nodes in the upper left that gives the redundancy of pathways. In case of a breakdown between node links, visualized by a yellow lightning bolt in Fig. 1 in the upper and lower middle networks, redundancy preserves pathways between A and B (upper-left network) and modularity isolates a group of nodes (bottom-left network). While modularity, redundancy, and diversity impact the resiliency of a system, less is known of the joint impact of these system-level properties. Tradeoffs between modularity, diversity, and redundancy is an important research frontier for social-ecological systems (Scheffer et al., 2012).

One of the main challenges of network research is its practical application at both the micro perspective of agency behavior and the macro perspective of a network's structural dynamism (Schweitzer et al., 2009). While many research results describe a network's topological configuration, e.g., as scale-free and hierarchical, however, these descriptions lack immediate implications at the agency level. Modularity and redundancy/diversity, on the other hand, are properties that may be more tangible and relevant to applications at the organizational agency level.

2.1. Diversity and Redundancy

Diversity has been found to contain three general properties (Sterling, 1994; Sterling, 2010): 1) variety, which refers to the available categorical types, for example, the number of species; 2) balance or evenness, which refers to the apportionment across available categories, e.g., distribution, where a more even distribution of categories indicates greater diversity; 3) disparity, which refers to the degree in which the categories themselves can be differentiated from one another. In previous literature, there is no mathematical representation that could incorporate all three properties of diversity. The Shannon-Weaver index (Shannon, 1948; Simpson, 1949) has been a widely used approach in the literature as it takes into consideration both variety and balance (Sterling, 2010). It is defined as:

$$H = -\Sigma_i p_i \ \ln(p_i)$$

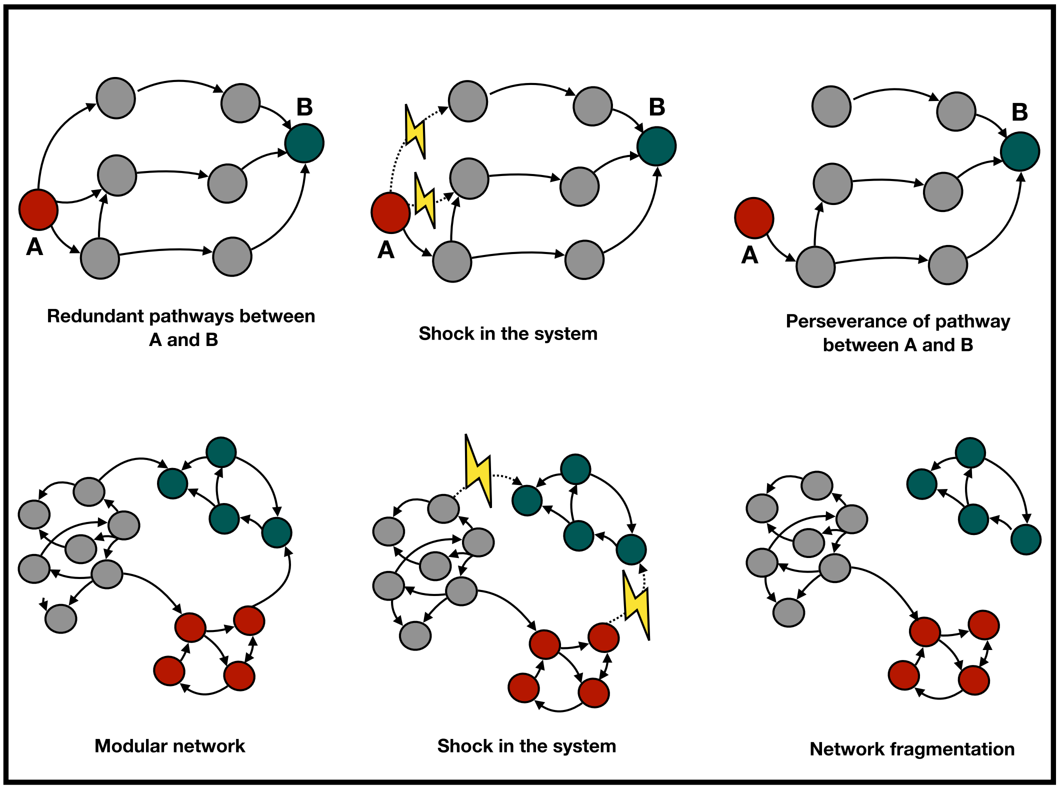
Here p_i indicates the proportion of category i within the total categories. The above formula can be rewritten in terms of systems process as:

$$H = -\sum \frac{T_{ij}}{T_{..}} \ \ln \frac{T_{ij}}{T_{..}}$$

Where, T_{ij} represents the effect that element i has on element j and the period signifies summation over that index.

From the above formulas it is evident that a higher value of H indicates higher diversity in a system. There is also a hierarchical aspect of diversity as expressed in the three types of ecological diversity. One considers genetic, species, and ecosystem diversity as necessary features for continued ecological functioning. In the micro-macro and perhaps *meso* scales addressed before, this includes the diversity of agents and network configurations - often expressed in terms of autocatalytic cycles (Gatti et al., 2018; Ulanowicz et al., 2014).

Information theory connects diversity and redundancy through a variable representing the efficiency of pathways within a network



Redundant pathways between A and B

Shock in the system

Perseverance of pathway between A and B

Modular network

Shock in the system

Network fragmentation

Fig. 1. Graphical representation of network modularity and redundancy. Each circle represents nodes in the system with multiple links representing pathways between nodes A to B. In case of a breakdown between node links, visualized by a yellow lightning bolt in the upper and lower middle networks, redundancy preserves pathways between A and B (upper-left network) and modularity isolates a group of nodes (bottom-left network).

(Ulanowicz, 2019), whereby the total system diversity (H) within a network is the sum of two antagonistic components, redundancy (ψ) and efficiency (A).

$$H = \psi + \mathrm{A}$$

In information theory, network efficiency (A) is represented by the average mutual information:

$$\mathrm{A} = \sum \frac{T_{ij}}{T_{..}} \ln \frac{T_{ij}T_{..}}{Ti.T.j}$$

and conditional entropy of a network system (Rutledge et al., 1976; R.E. Ulanowicz & Norden, 1990) is used to define redundancy (ψ) as:

$$\psi = -k \sum_{i,j} \frac{T_{ij}}{T_{..}} \ln \frac{T_{ij}^2}{T_{i.}T_{.j}}$$

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*).

Redundancy refers to the replication of pathways, functions, or components which enhances a system's fault tolerance ability. When faced with a shock or disturbance, additional redundancy, permits a system to continue a function without failure. Redundancy, however, does not necessarily benefit a reoccurring disturbance or a novel disturbance and the system may fail. Therefore, in addition to redundancy, a system may benefit from diversity. Diversity has important applications in any social-ecological systems. It can be defined as the degree of a system's variation. This may include functional diversity, i.e. the degree of the variations of the components which maintain similar functions, or response diversity, i.e. the degree of the variations of components representing different responses due to disruptions (Folke et al., 2004). Systems that maintain such diversities can be more flexible when faced with a disruption or shock. In natural sciences, diversity is seen as an essential component for ensuring flexibility which is also seen as a long-term survival strategy for natural ecosystems. Diversity is also critical for the perseverance and continuity of social and economic systems (Eagle, Macy, & Claxton, 2010; Grubb, Butler, & Twomey, 2006).

Although often in the environmental sustainability literature, network efficiency is preferred over network redundancy. For instance, systems are engineered to optimize resource use or minimize environmental pollution. But an extremely efficient system can become brittle and be prone to attacks. Thus, an optimal system may require a balance between being very efficient or highly redundant (Ulanowicz, 2019). As such, the concept of resilience provides a complementary perspective in understanding the desired sustainability of a system.

2.2. Modularity

Modularity is the property of a system whose components can be separated or integrated without any change within their properties or within those of the rest of the system. It was designed to measure the strength of the division of a network into modules. Systems with high modularity are better able to contain stress within a module without damaging other components. For example, consider how firebreaks in forest land management may break the spread of fire or how airport quarantines may prevent the spread of epidemics or invasive species or plants. In many different disciplines, modularity has received increasingly important attention and been adopted as one critical attribute referring to resilience. This includes, for example, ecological systems and food-webs (Krause et al., 2003; Levin, 1999; Stouffer & Bascompte, 2011), network science (Ash & Newth, 2007; Galstyan & Cohen, 2007), finance and economics (Barigozzi et al., 2011; Haldane & May, 2011; May et al., 2008), and socio-ecological research (Biggs et al., 2015; Carpenter et al., 2012; Walker & Salt, 2012).

Although the precise mathematical definition of modularity is challenging, previous researches have provided many methods for its measurement (Fortunato, 2010). The most commonly used method is the modularity maximization method (Girvan & Newman, 2002; Guimerà & Nunes Amaral, 2005; Newman, 1999). This method evaluates network modularity by comparing the number of links with a null network model, i.e., an equal number of nodes, links, and degree distribution but with random links among the nodes. Based on this, a modularity function is defined to measure the quality of the introduced partitions (P) as a community:

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

Here, $\frac{T_{i.} T_{.j}}{T_{..}}$ represents the probability of nodes i and j are connected. The parameter δ is Kronecker's delta, a 0–1 variable.

$$\delta_{c_i c_j} = \begin{cases} 1, \mathit{nodes\ i\ and\ j\ are\ in\ the\ same\ community} \\ 0, \mathit{otherwise} \end{cases}$$

The possible modular partitions are numerous for a given network. Using the heuristic algorithms, e.g., Tabu search algorithm (Glover & Laguna, 1998), spectral algorithms (Leicht & Newman, 2008), one can find the best fit of modular partitions.

3. Applications: Resource Trade Networks

One of the key networks of the modern age is an economic network. Specifically financial and commodity trade networks are increasingly fundamental to our collective energy, food, and development needs. The number and complexity of economic networks have grown with the development of globalization over the past few centuries and are increasingly vulnerable to the spread of shocks. The resilience of economic trade networks and the need to address system-level risks has become a subject of increasing attention in recent years, especially following the global financial crisis of 2007-2008, by policymakers and business practitioners. In this avenue, researchers have focused on understanding the structure of economic networks and their dynamics and response to shocks. Specifically, the application of modularity and redundancy towards enabling more resilient economic networks are promising research frontiers. There are two primary ways of accounting for resource networks 1) a top-down approach that uses input-output matrices to represent economy-wide transactions, 2) a bottom-up approach that uses published data on physical goods exchanges. Both types of networks are combined with environmental accounting methods such as life cycle assessment and footprint approaches to obtain embodied/virtual resource networks.

The modularity of financial networks can protect banks, firms, and other financial entities to limit the potential for cascading shocks. This can entail the splitting of banks or limiting the potential for contamination by constraining their activities to specific sectors or transaction volumes (Haldane & May, 2011). Changes to the level of modularity of global trade networks have important repercussions for the ability of the world economy to withstand and recover from economic shocks. Research on the network structure of world trade suggests that globalization has decreased the modularity of the world trade network, increased its sensitivity to economic shocks, and decreased the network's recovery rate (Fagiolo et al., 2010; He & Deem, 2010). Tainter (1988) speculated in his book, *Collapse of Complex Societies,* that due to the deep interconnectedness and loss of modularity a future major collapse would be global, as was observed in 2008, in contrast to the earlier collapses he studied that were regionally isolated. These findings emphasize the need for a better understanding of the risks and benefits of globalization and regionalization vis-à-vis economic resilience.

In addition to modularity, the redundancy of economic networks has important implications for their resiliency against shocks. Globalization, free trade agreements, regionalization, tariffs, and sanctions have been used to alter the redundancy of trade networks by increasing and or decreasing the preference of trade between partners. There is strong evidence in the ecological literature of a strong correlation between redundancy, i.e., the degree of network freedom and a system's capacity for resilience (Goerner et al., 2009). In a similar vein, research has indicated that economic sectors with higher redundancy can better withstand and recover from economic shocks (Kharrazi et al., 2017).

The scope of trade networks is not only limited to the direct flow of money or resources, but may also include indirect effects embodied trade of resources, e.g., embodied energy, water, pollutant emissions, land, and labor. Embodied networks do not directly incorporate the physical flow of goods, but resources and emissions resulting from their production and are therefore termed as embodied, embedded, enfolded, or virtual resource networks. The concept is useful in understanding and quantifying the environmental and social externalities of trade. For example, through the import of agriculture commodities, an importing country may avoid the environmental burdens of local food production by displacing it to the producing region**.** Although this may not be the primary reason as to why the trade arose, but rather comparative advantage, this could provide an interesting perspective to traditional trade theory.

Thanks to the maturing of multi-regional input-output (MRIO) database and environmental database and footprint concepts, one can study the embodied energy, for example, in trade among the world countries and sectors, by using the method of environmentally extended multi-regional input-output analysis (EE-MRIO). A typical example is the study of energy resilience on the global national level from the perspective of supplier diversity (including both direct and indirect energy suppliers) (Kharrazi et al., 2015; Sato et al., 2017). The energy diversities of different types of fossil resources can be measured for each country. In general, for any given country, direct energy imports have less diversity than the embodied energy imports. This is because the former reflects only directly traded energies between countries, while the latter reflects all traded goods with energy consumption between countries. Embodied energy import is a very important way of energy transfer in the form of non-energy commodities. Possibilities for the strategic utilization of embodied energy trade can be explored to compensate for the low diversity of direct energy trade.

Using the bottom-up approach, studies have analyzed international trade networks to address issues ranging from virtual water in global food trade to food safety and risk in mineral markets (Ercsey-Ravasz et al., 2012; Klimek et al., 2015; Konar et al., 2011). D'Odorico et al. used time-series data on food trade to assess the evolution of modularity in the global virtual water trade network (D'Odorico et al., 2012). However, the study's objective was on characterizing factors affecting virtual water trade and not specifically resilience. Using an alternate application of redundancy and Shannon Weaver index, Vora et al. (Vora et al., 2019) coupled trade networks with life cycle assessment to assess energy-water nexus tradeoffs in U.S. food trade. With an example of Texas, the study demonstrated that the current regional imports to Texas have a water scarcity risk embedded, but also have a potential to diversify imports from water-sufficient states and avoid interruptions to food supplies. However, the study reported that the same water-rich states also heavily relied on fossil fuels for irrigation and therefore posed a risk of increasing greenhouse gas emissions associated with imports.

While these studies provide important first estimates of network properties, the majority of trade network studies pertaining to sustainability and resilience are limited to descriptive network metrics. Compiling trade data and incorporating footprint approaches are data-intensive tasks in themselves, and transitioning from descriptive to prospective analysis is not always easily possible given a lack of temporal data, specifically at a regional scale (Vora et al., 2017). However, it is difficult to approximate the evolution of a network based on the internal properties of the network alone when only one, single, temporal snapshot of the network is available. A few studies have moved beyond descriptive analysis and applied time-series data to conduct prospective network analysis to understand the behavior and evolution of trade networks (Dodorico et al., 2012; Jacob & Kharrazi, 2018; Kharrazi et al., 2017; Suweis et al., 2011). However, more work is needed in this direction. In the absence of appropriate spatial and temporal data, alternate approaches could be employed including the use of null models for comparison (Vora et al., 2019), gravity equations (Tamea et al., 2014), and use of integrated models to assess future response to shocks(He et al., 2019). However, these tasks go beyond singular expertise or discipline. Therefore, more interdisciplinary discourse is needed to access novel data sources, e.g., remote sensing and survey databases, and to combine them with network, economic, and physical models to advance our understanding of the resilience of trade networks.

Finally, a particular issue faced both by top-down and bottom-up approaches pertains to trade data aggregation at the commodity level. In input-output networks, economies and countries are aggregated into representative sectors. Similarly, in trade datasets, the shipments are aggregated based on standard goods classification systems. The commodity aggregation often results in the networks being overly redundant or highly sparse depending on how the exchanges are recorded. Most graphs are nearly complete in that all nodes directly interact with other nodes at least in some small amount. This may distort network topology and characteristics, making it important to choose appropriate commodity coverage based on study objectives. However, when networks are weighted, the effective connectivity of a network is almost always much smaller than its topological connectivity and therefore effective connectivity can be used as a more accurate indicator (Ulanowicz, 2002).

4. Discussion and Implications for Public Policy

The application of systems-level network properties of redundancy/diversity and modularity requires strategic decision-making and targeted public policies. The structure of trade systems results from the multitude of actions and agency choices at levels ranging from the global (multilateral trade negotiations), regional (regional trade agreements), national (national trade policies) to individual levels (firms, manufacturers, shippers, households, and consumers). While some components within a system, e.g., nodes with high centrality, may maintain more influence than others, overall, the systems-level property of resilience would be determined collectively by individual agency contributions. Resilience is not only collectively determined but it is arguably a public good, whereby its benefits are non-excludable, non-rivalrous, and lead to positive externalities (Jacob & Kharrazi, 2018) and the emergence of network mutualism (Fath, 2007).

The benefits of a resilient trade system to shocks and disturbances are inherently non-excludable, e.g., a resilient food commodity trade network maintains a constant supply of food and is of benefit to everyone that partakes in the trade system. In the same vein, it can be seen that the benefits of a resilient trade system are non-rivalrous. Any particular group of people benefitting from the trade system's ability to return to a previous equilibrium or adapt to a new equilibrium after a shock or disturbance would not necessarily deprive other groups of people from benefitting from the same attribute of the trade system. In addition, a resilient trade system provides several positive externalities. Even if all participants did not invest adequately in resilience building measures, the benefit of a resilient trade system can be enjoyed by all actors participating in the trade system. This promotes trust in the global trading system and allows countries to produce goods and services reflecting their comparative advantage, while concurrently depending on their trade partners to meet their own consumption and production demands. Hence, applying the lens of provisioning a public good can help in understanding the reasons for the under-supply of resilience within critical human-systems such as trade networks and design policy responses (Jacob & Kharrazi, 2018).

In the ecological modeling literature, natural systems, e.g., food webs, tend to evolve towards higher resilience (which is termed as fitness or robustness), i.e., a balance between efficiency and redundancy (Ulanowicz, 2009). Similar to natural systems, trade theories also describe trade systems as evolving towards highly efficient network topologies. These trade theories range from the classical Ricardian theory of comparative advantage to the new trade theories where the role of imperfect competition, network effects, and increasing economies of scales are highlighted (Krugman, 1979). Hence, in new and classical theories of trade, greater trade integration leads to specialized centers of production and consumption and higher network efficiency. Concurrent with these trends, the increasing economic globalization of the past decades has made trade networks less modular and prone to cascading economic, public health, and financial shocks (Fagiolo et al., 2010). Therefore, evidence arising from the literature indicates a decrease of three important systems-level properties, i.e., redundancy, diversity, and modularity, of trade networks relevant to resilience. Therefore, building resilience, through focusing on related network-properties such as redundancy, diversity, and modularity, should be made an ex-ante consideration within trade agreements formulation.

In this light, public policies should better understand the topological trends of global trade systems and their repercussions on their resilience to potential shocks and disturbances. To improve the precision of relevant policies and strategies, more research is warranted in simulating and quantifying the impact of shocks on critical commodity trade networks. This can be achieved by collecting more precise datasets on commodity trade networks and examining their response to previous shocks and disruptions at higher temporal granularities including quarterly, monthly, and real-time data. Furthermore, a multi-stakeholder initiative raising the awareness of the risk of excessive network efficiency (low redundancy) and lack of modularity can lead to better management and contingency plans for the diversification of resource flows in anticipation of future shocks and disruptions. Investigation of these possibilities has already begun, e.g., see, for example, (Dave & Layton, 2020; Kharrazi et al., 2017; Kiss & Kiss, 2018; Lietaer et al., 2010; Panyam et al., 2019).

From the empirical study of the direct and embodied trade of energy, it is revealed that, for example, geopolitical tensions related to fossil fuels could be mitigated more effectively by strategically utilizing cross-border energy transfer in the form of embodied energy trade (Sato et al., 2017). For example, a country can shift its reliance towards embodied rather than direct energy imports. By taking policy measures to move its public and private sectors towards this shift, the country will be able to strengthen its energy security and resilience. Policies can also enhance energy resilience by improving the diversity of embodied energy imports. Thus, nations can reduce the cost to maintain their energy security, e.g., reduce the need to maintain extra storage for an unexpected disruption of direct energy supplies. By diversifying the cross-border resource transfers in the form of embodied energies, these countries could improve their economic and political positions. Similar arguments have been put forth for the importance of virtual water trade, where a water-scarce country can prioritize the use of valuable water resources by importing water-intensive goods from other regions.

There are some challenges in public policy for facilitating diversification of embodied resource portfolio. For example, while governments can influence the selection of direct energy suppliers to a certain extent, it would be difficult to influence directly the embodied energy trade network, as the categories of non-energy products are huge and their trade partners incorporate mainly private firms which will not be easily controlled by the government. In this setting, international trade policy, e.g., tariffs and trade agreements, could be used to indirectly influence the private sector. The analysis of energy diversity would be helpful towards improving energy resilience and facilitating well-informed decisions by policymakers. Similarly, energy-water tradeoffs can be managed with public-private partnerships. For instance, avoiding potential supply risks due to water scarcity may factor in a food company's decision when looking for suppliers. The government can work in conjunction by providing farming subsidies and incentives for upgrading irrigation technologies and moving away from fossil fuels to avoid unintended consequences. Nevertheless, policymakers should be wary of the rebound effect caused by the upgrading of irrigation technologies (Grafton et al., 2018).

5. Conclusions and Future Research

The three system-level properties of redundancy, diversity, and modularity are instrumental in determining the resilience of a system. While both modularity and redundancy individually impact the resiliency of a system, less is known of the joint impact of these system-level properties. It would be interesting for example, to evaluate where if in combination, pair-wise or as a triple threat, these system properties are antagonistic, whereby, their joint impact could be less than the greater of their individual impacts. For example, tradeoffs between modularity and redundancy is an important research frontier for social-ecological systems (Scheffer et al., 2012). Towards this end, future research should focus on the theoretical relationship between redundancy and modularity and measures of resilience, such as time to 'bounce-back' within the context of specific social-ecological systems, or the contribution of redundancy and modularity to resilience preparedness along the adaptive cycle (Fath et al., 2015). One possible research direction can be to generate a series of random networks and examine the relationship between the generated modularity, diversity, and redundancy properties through regression analysis or blackbox modeling methods, e.g., artificial neural networks (Hassoun, 1995) or grey modeling (Julong, 1989; Tseng et al., 2001). Furthermore, with the increasing availability of diverse open datasets, embodied resources, e.g., energy, water, and phosphorous, in trade can be studied on not only the national level but also on the regional or urban level. On this basis, one can examine the efficiency, redundancy, resilience, and modularity for embodied trade networks. These results should in turn inform the international public policy discourse on rule setting on critical systems such as trade.

Disclaimer

The views expressed herein are those of the authors and do not necessarily refelect the views of the United Nations.

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