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The Importance of Collaboration in Creating Climate-Resilient Supply Chains

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Abstract: Global resource supply chains connect dissimilar locations and economies by transporting goods like fish, rice, and minerals from producers to consumers worldwide. Although these supply chains are more sensitive to the effects of a changing environment, the study of the production phase pays little attention to them. Too frequently, businesses discover if and how their supply chains can resist and recover from climate shocks via experience, with little knowledge of how to proactively design supply networks that are climate resilient. Hence, using a network-based modeling technique, this study evaluates supply chain resilience, specifically the interruption encountered during severe climate-related events.

This study examines supply chain examples from the food processing, agricultural, and mining sectors of America's resource industries, all of which have recently been impacted by climate shocks. For each industry, we create four supply chain indices to measure how well simple and complicated supply chains perform based on evenness, resilience, continuity, and climate resilience. It demonstrates that complex supply networks with many nodes and linkages are more robust to interruption than natural systems. Importantly, if climatic shocks increase in frequency, all chains, regardless of their complexity, will lose resilience. This emphasizes how crucial it is to take into account the larger economic advantages of varied chains, which may reduce risk and enhance the design after a disruption. It also highlights the value of a systems approach to risk management in supply chains, especially when taking into account adaptation options for dealing with direct and indirect consequences on the chain as well as the global problem of lowering greenhouse gas emissions.

Keywords: Gas Emission, Precipitation, Climate Resilience, Supply chain, network-based

I. INTRODUCTION

Due to the effects of climate change on supply chain management, concerns have been raised about how firms can adapt to changing weather patterns, changing landscapes, and varying resource availability (Ghadge et al., 2023). Companies are working harder to build supply networks that are resilient to climate change so they can withstand and adapt to its effects.

Thus, the significance of initiatives to build climate change resilience in supply chain management has risen due to the triple threat of climate change, biodiversity loss, and food poverty. If companies wish to build a safe, secure, and sustainable food supply chain in the face of these dangers, they must prioritize traceability and water management protocols while integrating crop management practices that are sensitive to climate change into their operations. Improving functional crop diversity and soil nutrient management and preserving soil humidity are some of the techniques for crops and soil management to mitigate the effects of climate change (Ghadge et al., 2023).

Organizations are progressively emphasizing sustainable supply chain management to adapt to environmental changes, increase operational effectiveness, and gain a competitive edge (Accenture 2010; Awodiji et al, 2022; Brandenburg et al. 2020; Sarkis et al., 2011). To manage resource allocation, productivity, and climate resilience in this environment, businesses are investing in renewable resources, improving energy consumption practices, and researching the potential of smart agriculture.

Businesses have been under persistent and demanding pressure to identify and implement supply chain management as a vital step in obtaining lasting competitive advantage as a result of globalization, greater outsourcing, competitiveness, and ongoing changes in the market's dynamics (Lee, 2002). The advantages of using supply chain management concepts have been extensively demonstrated in research and literature (Oke and Gopalakrishnan, 2009). Organizational supply chains are now more susceptible than ever before to these changes and the results of numerous unanticipated events due to the global nature of today's supply chains and the increased inter-organizational dependence (Norrman and Jansson, 2004; Sheffi, 2005; Wagner and Bode, 2006).

Supply chain vulnerability, as defined by Christopher and Peck (2004), is "an exposure to serious disturbance, arising from risks within the supply chain, as well as risks external to the supply chain." It is abundantly clear from this description that a supply chain may face risks from inside the company, from within the supply chain, from within the network of the supply chain, or from outside the supply chain organization. This shows the vast range of vulnerabilities that today's supply systems face, underscores the need for careful management of these risks, and illustrates the significance of supply chain resilience (SCR).

This paper contributes to the phenomenon of SCR based on climate change by emphasizing transferable lessons on human resource management, redundancy, avoidance, collaboration, culture, agility, flexibility, and decision-making that may help accomplish SCR. An overview of the literature on SCR and climate change is presented at the beginning of this paper, followed by a critique of the methods, results, and measurements. The presentation and discussion of the results are followed by the introduction and description of the framework for flexible decision-making. The study concludes by identifying its limitations, detailing its implications for practice and research, and making recommendations for more investigation.

1.1 Related Studies

Climate Change

The term "Greenhouse Effect," which explains how climate change occurs, describes how the existence of an atmosphere containing gas that absorbs infrared radiation causes a planet or moon's thermal equilibrium temperature to vary (Bolin and Doos, 1989). More specifically, it is a physical process that occurs on Earth, where a portion of the thermal radiation released by the land and ocean is absorbed by the atmosphere and reflected on the planet (Mitchel, 1989).

The cause of climate change is human activity (anthropogenic) (Berrang-Ford, Ford, and Patterson, 2011). It is brought on by global warming, which in turn is the consequence of certain human activities, such as the burning of fossil fuels, land use changes that occurred after the Industrial Revolution in the middle of the 18th century, and other environmental degradation activities (such as deforestation and anti-wildlife activities). These activities produce excessive amounts of carbon dioxide ($CO_{2)}$ and other environmentally harmful gases, such as greenhouse gases (GHGs), which absorb part of the thermal radiation emitted by the land and ocean and reradiate it back to Earth (Mitchel, 1989).

The Earth's climate is significantly impacted by the effects of global warming. Every inhabited region of the Earth produces emissions, but some nations, particularly the industrialized ones and some of the growing economies, most notably China and Qatar, emit a disproportionate amount of GHGs overall. Figure 1 (EIA, 2022) shows the top 10 worldwide CO_2 emitters' combined and per-capita emissions for the year 2021 in more detail.

As can be seen, Qatar and Bahrain are by far the largest emitters of GHGs, contributing 35.59 and 26.66 metric tons of CO_2 annually, respectively. China has made progress toward becoming a climate-friendly nation, generating 8.0 metric tons of carbon dioxide annually, down from creating one-fifth of the world's annual CO_2 emissions between 2017 and 2020 (ICPC, 2021). However, carbon dioxide is the main heat-trapping gas, and its emissions are increasing quickly. However, in terms of emissions per person, Americans create 19.8 metric tons of CO_2 annually, compared to Chinese residents who emit an average of 4.6 metric tons annually, which is roughly comparable to the global average (IPCC, 2007).

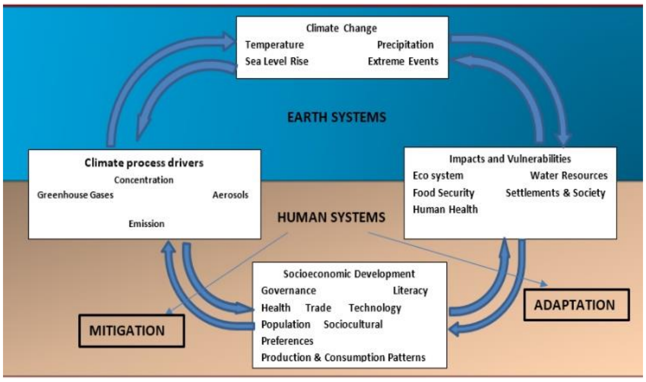

Fig 1. Anthropogenic Schematic Framework of Climate Change (Source. IPCC, 2007)

Radiative Forcing

In terms of climate science, the term "radiative forcing" (RF) refers to the shift in net irradiance at the tropopause (Shine et al., 1990). In clearer terms, RF is the difference in radiance at the stratosphere/troposphere border. Bellouin et al., (2020) explained that the troposphere is the lowest layer of the atmosphere, extending from the surface of the Earth to an average height of 10 km at mid-latitudes (up to 16 km in the tropics and 9 km at high latitudes), and is where clouds and other meteorological events develop. Temperatures in the troposphere often drop with height. The highly stratified area of the atmosphere above the troposphere is known as the stratosphere (Bellouin et al., 2020), and it ranges in height from approximately 10 km (on average, 9 km in high latitudes and 16 km in the tropics) to about 50 km. In a certain climatic system, "Net irradiance" is the difference between the radiation energy that enters and leaves the atmosphere. It is expressed in Watts per square meter. The change is the measured variation from 1750, which is considered the official beginning of the industrial age (Shine and Forster, 1999). A positive force tends to warm the system whereas a negative force tends to cool it (more energy is expended than is brought in). Changes in insolation, the quantity of solar radiation reaching the Earth, or the impact of changes in the amount of radiatively active gases and aerosols present are two potential causes of RF. Unless otherwise stated, RF for the IPCC refers to a worldwide and yearly average value (Source. Change, 2014).

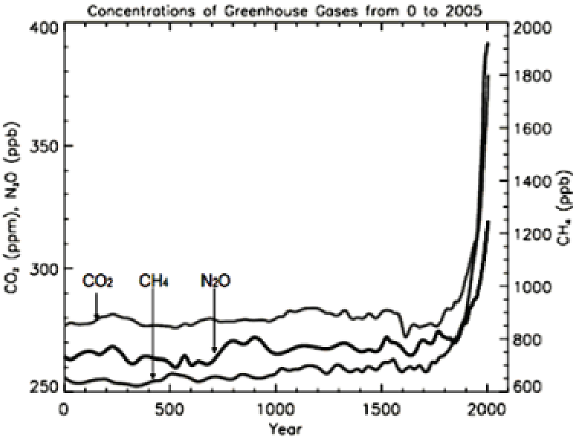

Fig 2. Levels of Greenhouse Gases in the Atmosphere over the Past 2000 Years. (Source. Herzog et al., 2000)

Supply Chain

There are several definitions of a supply chain, one of which is depicted below. The simplest definition is provided by Lambert et al., (1998): a supply chain is the coordination of businesses that market goods or services. According to (Handfield & Nickols, 1999), the supply chain includes all activities connected to the flow and transformation of goods from the stage of raw materials (extraction) through to the end user, as well as the associated information flows. This definition reflects the supply chain's broader scope. The supply chain is characterized by an upward and downward movement of commodities and information. Another definition is provided by Ganeshan & Harrison, (1995), who define a supply chain as a network of locations and distribution choices where the tasks of material procurement, material transformation into intermediate and finished products, and finished product distribution to customers are carried out. The partners involved in a supply chain are specifically stated in the definition provided by Chopra and Meindl (2001). A supply chain is made up of all steps that are therefore directly or indirectly engaged in completing a client request. Along with the producer and suppliers, it also comprises transporters, warehouses, retailers, and actual customers.

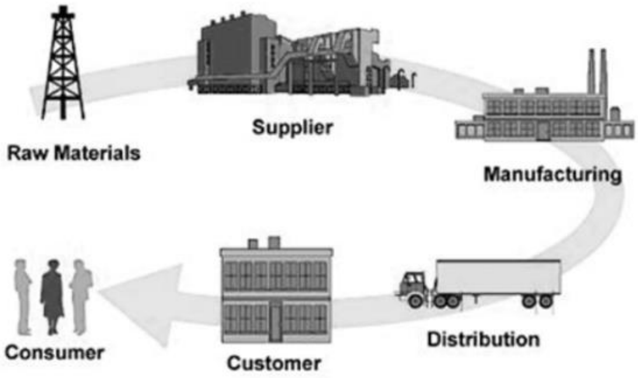

Fig 3. Supply Chain Concept

Despite being frequently associated with logistics and logistics management, it is believed that SCM should be distinguished from the latter (Bolstorff and Rosenbaum, 2023). As a result, while logistics refers to the set of processes necessary to move and position inventory throughout a supply chain, SCM, as defined above, is the coordination of production, inventory, location, and transportation among the participant links in a supply chain to achieve the best mix of responsiveness and efficiency for the market being served. As a result, logistics is a subset of the larger supply chain architecture and performs its tasks inside it as inbound (within the confines of a certain organization, which is a link in the supply chain) and outbound (beyond these confines) logistics (Rajasanthi and Muthuswamy, 2022). Additionally, logistics is the procedure that adds value by coordinating and placing inventories (Sweeny, Grant, and Mangan, 2018). Order management, inventory, transportation, warehousing, materials handling, and packaging are all combined into one process that is connected throughout a network of facilities. The complete supply chain is linked and coordinated through the integration of logistical operations, which boosts the efficiency of the chain overall.

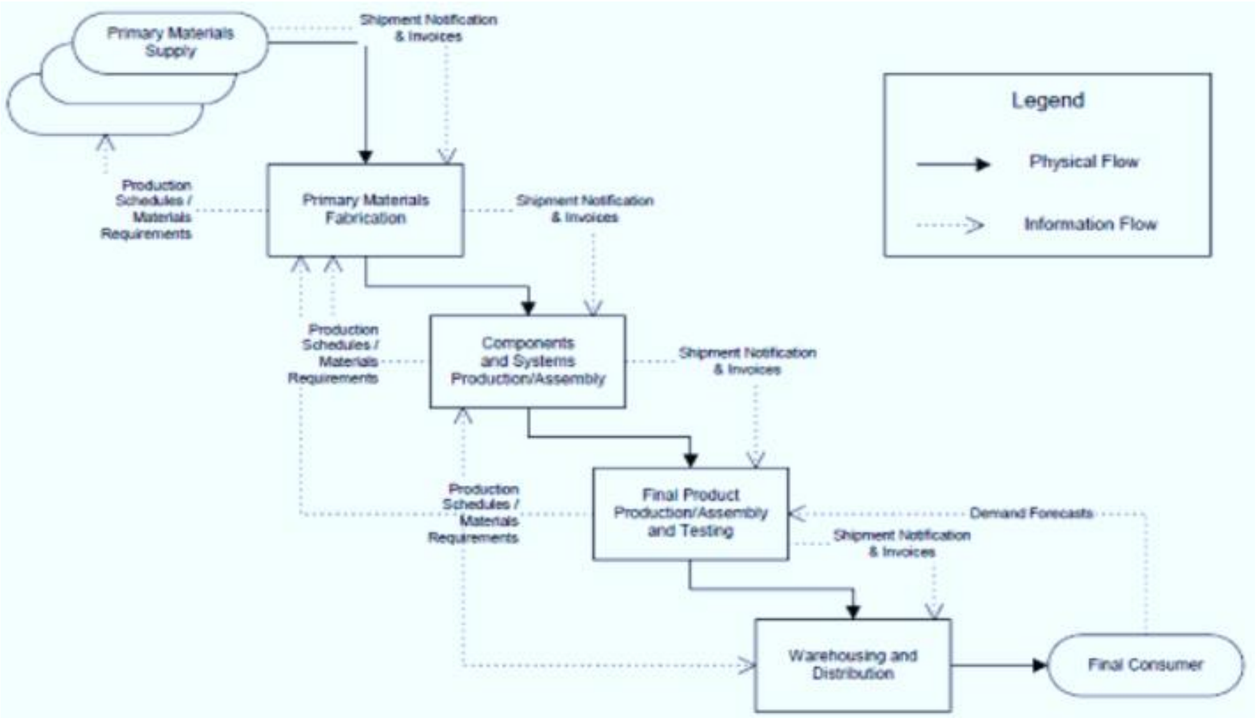

Fig 4. Supply Chain Process (Source. Bolstorff and Rosenbaum, 2023)

In conclusion, logistics is "the process of strategically managing the procurement, movement, and storage of materials, parts, and finished inventory (and the related information flows) through the organization and its marketing channels in such a way that current and future profitability is maximized through the cost-effective fulfillment of orders" (Christopher, 1992), to use a commonly cited definition (Harland et al., 1999, p. 661).

Over time, firms have increasingly looked to improve the efficiency of their supply chains by evaluating two key types of transactions (White et al., 2004):

Real-time flow (physical): members of a supply chain are connected by physical flows of material, which move "forward" from suppliers to consumers at each link in the network. In most supply chains, value is added along the way as the physical flows go from raw materials through intermediate components and assemblies to completed products.

Data flow (information): as orders for goods, services, components, and supplies are placed, most data travels "backward" from customers to suppliers. As a result, payments are made, which causes money flows to occur as well. Although each link in the supply chain has unique information and logistical requirements, all linkages require some information (such as long-term sales and production projections) for capacity planning and procurement.

Supply Chain and Climate Change

While supply networks play a key role in global warming, climate change is the root cause of phenomena that can have serious effects on supply chains, such as extreme weather occurrences. Such effects are felt throughout the entire set of supply chain operations, including production plants and manufacturing processes more generally. The location has a significant impact on how vulnerable plants and production processes are in terms of infrastructure, personnel, communications, supply, etc., to the point where, in some circumstances, relocation may be the only way to address issues brought on by extreme events and other climate change-related phenomena like floods, sea level rise, storms, hurricanes, etc.

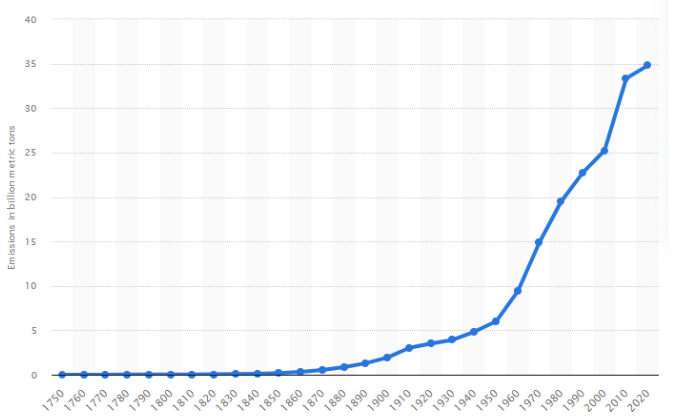

Fig 5. Global Emission in Billion Metrics from 1750-2020 (Ritchie et al., 2020)

The Carbon Disclosure Project-6 (Zilinski, 2008) outlines the range of physical dangers brought on by climate change that can impact the operations of the sector as a whole. The identification of physical hazards that might have an impact on business includes temperature changes, floods, a rise in storm frequency and severity, a scarcity of water, the spread of illnesses, and modifications to regional weather patterns. The industry's automotive sub-sector looks to be particularly vulnerable to hazards to its reputation. Given the widespread agreement that vehicles as they are now designed directly contribute to the atmospheric concentration of CO_2, automakers must be perceived to be acting and offering solutions to this problem. Then, customers will effectively provide the business with a "license to operate".

Risks to a company's reputation may have a detrimental effect on hiring and employee retention. This, as the research notes, is a crucial element in a changing market: if manufacturers are to create the technologies and goods essential to compete in a low-carbon world, they must be able to continue to attract and hold onto the requisite talent. A segment of the climate change industry already provides a selection of green goods that aid customers in lowering their carbon footprint (De Melo, and Vijil, 2016). The sector has also recognized rising energy and raw material prices as a significant issue. As a result, conserving energy is encouraged. Zilinski (2008) asserted that there will be both danger and opportunity as the regulatory and consumer behavior landscape in the manufacturing industry evolves.

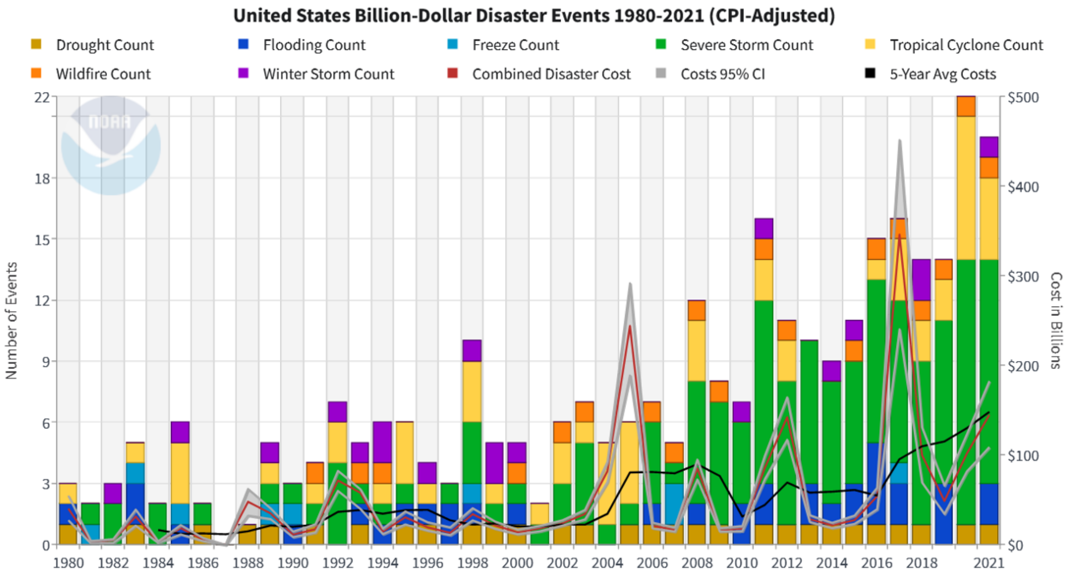

Fig 6. Weather and Climate Disasters Worth Billions in America (Source. NCEI and NOAA, 2022)

In 2022, the US had 18 major climate disasters and each costing approximately $1 billion (NCEI and NOAA, 2022). Around 85% of the coal mines in America were reportedly impacted, and as a result of the incidents, many of them carried on with decreased capacity for more than a year (Shuang-Ye, 2023).

II. METHODS

To investigate the impact of climate intrusions on supply chains, a comparative case study approach has been developed. To investigate how climate invasions affect the supply chain, a comparative case study methodology has been established. This study's mapping, derivations, and modeling would be significant in light of the comparison of these two concepts. The method focused on three resource sectors which are agriculture, food processing, and mining. Using data from Plagányi et al. (2014), we distinguish between "simple" and "complex" supply chains in this research using an empirical definition based on the quantity of linkages and nodes in each chain as presented in the Appendix. Consider the number of linkages per node as a first-order definition of complexity. In this section, it is explained how supply chains are mapped as well as the modeling techniques used to calculate shock resilience.

Mapping Supply Chains

For purposes of comparability, the supply chains for the chosen cases in this study were built using a consistent framework from earlier research (Lim-Camacho et al., 2015; Plagányi et al., 2014; van Putten et al., 2016). This identifies six to nine general steps from manufacturing to the point at which each supply chain concludes. The precise stages of the chain vary between sectors (Lim-Camacho et al., 2017), but they are most constant in both sector case studies.

The two mining case studies, for example, traveled from pit to port in contrast to the food processing and agricultural case studies, which proceeded from production to family consumption. This stage of the method tried to ensure consistent selections for the amount of aggregation, impacted also by our wide category titles. To identify nodes, it was useful to combine individuals who are physically close to one another or who are otherwise believed to be similarly at risk of a climatic shock interrupting the supply chain. This study determined the number of nodes *n*, the number of linkages *L*, and the *SCI* as a measure of "connectance" for each supply chain. Lower numbers denote more connectivity. A higher number denotes disconnection.

Assessing Impacts and Predicting Supply Chain Resilience

This modeling strategy was developed by Plagányi et al. (2014) to examine how these supply networks were affected by external factors such as climate shocks and severe occurrences. The Supply Chain Index (SCI), a quantitative indicator that they developed, is obtained by first determining a meter for each node in the manner shown below:

$$\mathbf{SCI_j = \Sigma^{n}{}_{i-1} S_{ji}P^{2}{}_{j}} \qquad \text{(Eq 1)}$$

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The ratio *SJI* of the total product that receiver *j* gets from supplier *i* compared to all goods flowing into that element *j* in the equation above reveals the supply chain elements *j* that have high throughput rates *Pj* and improved connection. The supply chain's overall standardized Supply Chain Index (SCI) is calculated by averaging individual *SCIj* scores and dividing by *L*:

$$\mathrm{SCI}_j = \Sigma^{n}{}_{i-1}\,\mathrm{SCI}_j/_{\mathrm{L}} \qquad \text{(Eq 2)}$$

This calculation is significant because the early detection of these components might result in the creation of adaption methods that lower the risks associated with potential climate change or other supply chain management disruptions. In the network-based method, the number of components (or nodes) and links (or connections) are counted, and the resultant 'inflow' proportion is squared to give greater weight to high throughput, which denotes significant system routes (Plagányi et al., 2014). The metrics and fundamental studies performed on each supply chain are described here, followed by simulations that aim to cut out unnecessary linkages to examine the effects of different interruptions.

Generating Supply Chain Metrics

Each simulation included the calculation of four metrics: evenness, resilience, supply continuity, and climatic resilience. Indicating how well the risk is distributed across the supply chain as opposed to being concentrated in a few important pieces, the evenness score measures how equally distributed the different nodes are in terms of their unique SCI ratings. We employ Simpson's Diversity Index ED (Simpson, 1949), which is defined as follows, to assess the evenness in terms of the variance of individual node SCIi values

$$\Sigma_{\cap}\frac{\mathbf{1}}{\mathbf{z_J}\left(\mathbf{sc_I}/_{\mathbf{sc}\,\mathbf{1}}\right)}\mathbf{2}\times\frac{\mathbf{1}}{\mathbf{n}} \qquad \text{(Eq 3)}$$

SCI_j is the supply chain score for node j, which is divided by the overall SCI to compute the proportionate contribution, and n is the total number of supply chain nodes or elements. An evenness index with a scale from 0 to 1 (maximum evenness) is produced by dividing the evenness by the number of nodes n. The derivation of the SCI is based on Simpson's variety Index (Simpson, 1949), which also offers a simple way to gauge how evenly distributed a group of linked components is. Therefore, the resilience measure score is calculated as 1 SCI, where higher values represent increased resilience. Hence

$$.\!:\ \textit{resilience} = 1 - \textit{SCI} \qquad \text{(Eq. 4)}$$

Third, if one node is affected by a shock (such as a climatic extreme), the continuity of supply meter measures the percentage of the base case product flow that is still able to flow across a disrupted supply chain, thus:

$$.\!:\ \textit{continuity} = P^{*}/P \qquad \text{(Eq. 5)}$$

Finally, we construct a combined climate resilience measure (CR) as follows to assess the relative resilience to climate and other shocks in terms of both changes to the overall resilience of the supply chain structure and impact on the continuity of supply.

$$.\!:\ \mathrm{CR} = \textit{continuity} \times \textit{resilience} \qquad \text{(Eq. 6)}$$

Between 0 (no climate resilience) and 1 (highest climate resilience), the range of CR values. This last parameter is crucial since the supply chain's overall volume of items moving through it and its organizational structure both matter.

Supply Chain Disruptions Simulation

In the beginning, the simulation model randomly selects a node that is assumed to be dormant that year. The simulations then repeatedly track through all links in the supply chain to determine whether and how the product may be diverted down different routes, doing so until it reaches the final users. The SCI is then updated to account for the network configuration changes brought on by the shock of the climate, and the change in the end product that is delivered to customers is also calculated. Since sub-time step nodal recovery dynamics are not taken into account in the simulations, they reflect worst-case scenarios in which a node stays inoperative for that time step (i.e., a year). The effect is also considered to be the same if the climatic shock lasts longer than a year.

To compare the perturbation scenario outcomes with the base case scenario and the key element scenario, in which the key element is presumably missing, the median, standard deviation, and range from the 100 simulations are computed. For two perturbation case situations, the statistics for random and key element disruptions are computed:

1. Node is eliminated every 5 years.
2. One node is eliminated per year by comparing the study's findings to prior research by Plagányi et al. (2014) and data on other processed food supply chains.

Food processing data were obtained from earlier research (Pawar and Mali, 2020; Khan et al., 2020), and they were augmented with further data obtained through interviews with important chain participants and by data reliant on food processing (Wunderlich and Smoller, 2018).

III. RESULTS

Agriculture

Price volatility has increased 30–40% during the past ten years compared to the preceding ten, in part as a result of climate-related stocks such as droughts, floods, storms, and fires (Ray et al., 2015). According to methods projection, volatility of agricultural produce (particularly rice in America) is predicted to increase, partially as a result of climate change as seen in the nodes report of 0.855 and 0.929 simple and complex chains respectively

Therefore, industries need to adjust at both the production level and throughout the whole supply chain. Despite the increase in rice yield in America, the supply of this stipple crop is affected basically due to precipitation. Below is a representation of crop acreage drop in rice grains in America due to climate change as derived from this study's nodes calculations.

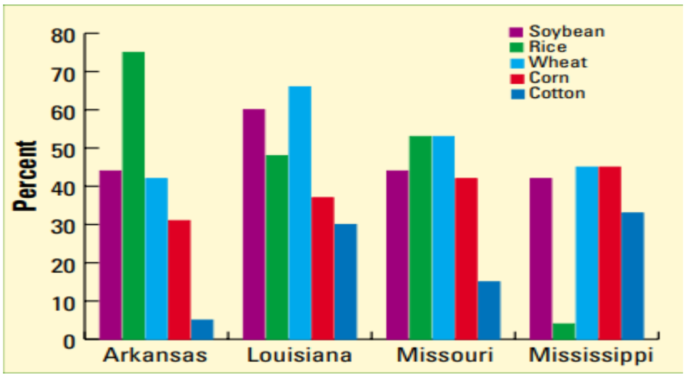

Fig 7. Crop Acreage Based on Resilient Scores

Food Processing

Based on a resilience score of 0.95 and 100% product throughput, the climatic resilience score (CR) determined for the processed food simple supply chain under normal conditions (base) is 0.95. The supply chain for the processed food complex, on the other hand, has more climatic resilience and has the highest baseline CR score (0.98), indicating greater resistance to shocks. In a one-in-five-year shock scenario, CR for the simple chain falls to 0.91 as opposed to 0.95 for the complicated chain. Both chains are more significantly impacted by annual shocks, with a CR of 0.77 (simple) and 0.85 (complex) as a result. The CR (simple) is 0.83 in scenarios with one-in-five-year shocks to the essential element, but it is significantly lower under an annual shock scenario, at 0.36 compared to 0.56 for the complex chain.

Mining

Of all the supply chains analyzed, the basic mining supply chain has the lowest baseline CR score (0.79). The one-in-five-year shock scenario (CR = 0.73) and yearly shocks (CR = 0.48) both marginally lower this score. The chain's CR score is reduced to zero if important factors are impacted yearly. The difficult mining case, on the other hand, has one of the highest baseline CR ratings (0.96). CR is marginally decreased (0.89 in the one-in-five-year shock scenario) and significantly decreased (0.61 in the yearly shock scenario). The CR score of the complicated mining chain is roughly 50% of the baseline value (0.49) if critical pieces are affected yearly.

In general, complex supply chains outperform simple supply chains in terms of CR scores (Figs. 8 and 9). Calculations of the standard deviation reveal that yearly shocks have a far more varied influence than shocks that occur once every five years. This suggests that the impact on the flow of goods through the supply chain may be modest or enormous, depending on the node impacted. Annual shocks to critical factors often cause at least 50% less merchandise to move through the supply chain. There are also situations where there is no product flowing through the chain, such as in the basic mining chain when there are yearly shocks to the main ingredient. One-in-five-year shocks on random nodes or important components do not significantly restrict the flow of products through the supply chain system.

Baseline Supply Chain Metrics for Results

A variety of metrics based on the volume of product throughput, number of nodes n, and number of linkages L are used to describe the case study supply chains. The Plagányi et al. (2014) SCI, which illustrates how heavily a chain depends on a select few essential components, serves as the foundation for these measurements. Here, we provide the outcomes of the baseline measures, which show how supply networks function when they are not disturbed. The appendix displays a summary of the findings for all supply chain parameters. Higher evenness ratings suggest a more uniform distribution of risk among supply chain nodes. Higher scores indicate reduced reliance on critical chain components for food processing, rice (agricultural simple), iron ore (mining complicated), and diamond (mining simple) chains. The lower evenness score for the post-flood rice chain (agricultural complex) indicates that the risk within the chain is mostly carried by its primary components, Lundberg, Texmati, and foreign markets.

Agriculture Supply Chain

The basic agriculture supply chain scored 0.34 for evenness and 0.855 for resilience. American Grains Storage (AGS), the only corporation that stores grains after harvest, is the chain's primary component, followed by domestic rice producers and international importers. The evenness score for the complex agriculture chain was 0.20, whereas the resilience value was 0.93, which was greater. The basic supply chain has a more level spread of risk, according to evenness ratings, in part because it contains fewer nodes than the complicated network does. However, the complex chain has better resilience values. The need for brown rice, white rice, and foreign importers are the main components of the complex agriculture supply chain, just like they are for the simple chain.

Mining

The basic mining supply chain received a score of 0.79 for durability and 0.34 for evenness. Conveyors, on-site processing, and industrial sorting are essential components. The complicated mining chain received a score of 0.96 for robustness and 0.52 for evenness. The distribution of risk is more evenly distributed, and the network as a whole looks to be more resilient since the complex mining chain's evenness and resilience ratings are both higher than those of the simple mining chain. Transport-related nodes, such as Rail Corporations, road/conveyor, and sole-use rail, are important components of the complicated mining chain.

Food Processing Supply Chain

The basic food processing supply chain scored 0.26 for evenness and 0.952 for robustness. This supply chain's three essential components were General Mills, the procurement of raw materials, and exporters. Of all the supply chains examined in this study, this chain had the best resilience and evenness ratings.

Resilience Results of Simple and Complex Supply Chains

Complex supply chains regularly score higher in terms of resilience than simple supply chains, according to analysis (Fig. 4). Simple mining (diamonds) and simple agriculture (rice during a drought) function with the simplest and most streamlined structures, with the fewest nodes (12 and 13, respectively) and linkages (both 15). These two supply chains have the lowest resilience ratings. The two supply chains with the most linkages per node—the food processing and sophisticated mining chains—are thought to have the highest levels of resilience, with the extra links to nodes offering more operational alternatives in the event of system shocks.

Simulating Shocks and Their Impacts

Climate resilience (CR) for each chain refers to the product's capacity to move through the chain in the face of simulated yearly shocks that result in the loss of a node from the system.

Agriculture Supply Chain

The baseline CR for the pre-drought basic agricultural (rice) supply chain is 0.85. CR marginally decreased to 0.83 under a one-in-five-year shock scenario and to 0.74 under an annual shock scenario. When the crucial factor is compromised, this decreases to 0.73 for every fifth year and 0.19 for shocks that occur annually. The baseline CR for the complex agricultural (rice post-drought) supply chain is 0.93; in a one-in-five-year shock scenario, it drops to 0.92; and if the key element is impacted, it drops to 0.80. If shocks happen every year, CR is high (0.89), but if the important factor is affected, CR is significantly lower (0.24). These findings show a strong dependence on essential components in both basic and complicated agriculture supply chains.

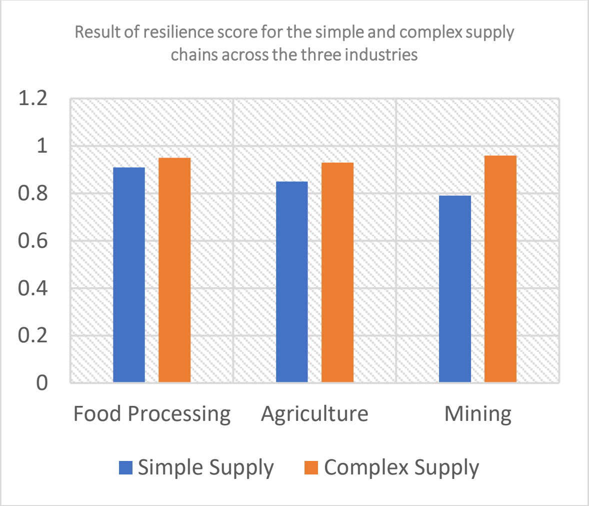

Fig 8. Result of resilience score for the simple and complex supply chains across the three industries

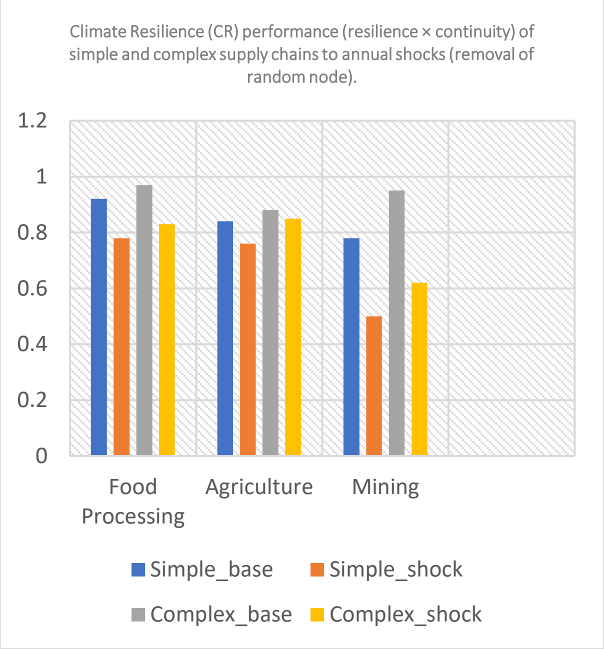

Fig 9. Climate Resilience (CR) performance (resilience × continuity) of simple and complex supply chains to annual shocks (removal of the random node).

Discussion and Representation

Resource-based sectors will be more affected by climate change than just the manufacturing stage, with supply networks at all levels potentially being disrupted (IPCC, 2012, 2013, 2014). With the assumption that these shocks would randomly affect any node in the system, the network-based study here quantifies the impact of climatic shocks on six supply chains, whether they are regular (i.e., every year) or periodic (i.e., once every five years). It is difficult to comprehend how resilient these representative supply chains are, which emphasizes the necessity to employ a variety of measures to reflect complicated dynamics inside a network.

This study reveals that complex supply systems, frequently those with a significant number of nodes and linkages, are more resistant to disruptions similar to those projected under climate change. It does this by simulating supply chain disruptions through simulation. The findings also indicate that when disruptions grow more frequent, all chains, regardless of how complicated they are, will become less resilient, especially if crucial components are affected annually. Typhoon Haiyan, Hurricane Sandy, and the 2011 floods in Thailand and Queensland (Cai and van Rensch, 2011;

Haraguchi and Lall, 2015; Levermann, 2014; Rosenzweig and Solecki, 2014; Wai and Wongsurawat, 2012) serve as examples of how extreme events can cause supply chains to break down on a large scale.

Supply networks will need to be modified to minimize significant disruption as extreme events are predicted to become more frequent and severe due to climate change. In certain cases, tiny adjustments or gradual alterations might strengthen the chain's resilience and lessen the effects of interruptions. Increased resilience to shock events may result from the addition of more cross-connected nodes, such as those that offer alternate product paths in basic supply chains. The measurements created here can be used as indicators to examine how supply chains might become more resilient and adaptable to future climatic shocks. They may also offer guidance for better reorganization after a disruption.

However, there may be situations where making business decisions necessitates a whole transformation of the boundary conditions and corporate objectives (Jakku et al., 2016; Rickards and Howden, 2012; Rippke et al., 2016). As in the straightforward mining scenario given above, where yearly shocks to the critical ingredient prevented any product from moving down the chain, supply networks may no longer be functioning if large-scale changes or significant shocks signal that risk tolerance levels have been surpassed. Significant adjustments would be necessary to maintain viability. The indicators can show the effect on profitability and guide strategic choices depending on the level of business risk that is acceptable.

A supply chain redesign, where the dependency on key nodes is controlled to better disperse risk, maybe a feasible choice for adaptation in the event of a basic supply chain (van der Vorst and Beulens, 2002). Before the execution of the redesign, the supply chain measurements may be utilized to simulate how robust a suggested network may be. The SCI measure (and the derivatives used here), as described in Plagányi et al. (2014), offers a consistent and impartial collection of metrics for assessing and comparing supply networks, although the interpretation depends on several variables and the context of specific supply chains. Below are graphs comparing the CR scores of both supply chains of the industries against the normal supply base.

In this paper, we suggested additional measures for measuring supply chain resilience. First, since the SCIj (Eq. (1)) indices help identify essential components that should be the focus of adaptation efforts, we kept using them for individual supply chain nodes. Second, we established a Resilience score for a whole supply chain as 1 SCI (where the standardized SCI index is obtained using Eq. (3)), with this overall index for each chain serving as a standard approach to compare various chains. Third, we created an evenness index (Eq. (3)) that measures the evenness in terms of the variation in SCIi scores for particular nodes and, as a result, shows how evenly distributed risk is across a network. The basic agricultural and mining cases, which both had excellent evenness scores but also had the two lowest resilience scores, serve as an illustration of the value of employing many indices by showing that evenness alone is insufficient for determining the supply chain's resilience. Finally, we created a climate resilience metric (CR) (Eq. (6)) in recognition of the significance of both the supply chain's structure and the overall volume of goods that pass through it. This is a more complete measure of the relative resilience to climate and other shocks than the resilience score alone and is just the product of the network's resilience score and its continuity score (Eq. (5)).

As with any socio-ecological system, managing supply chains in practice entails assessing several features and perhaps resolving tradeoffs between intended management objectives (Walker et al., 2004). Similar to mitigation, supply chain adaptation may be challenging due to measures performed at one node of the chain have both intended and unintended detrimental effects on another node, as well as the possibility of conflicting sustainability and mitigation objectives. For instance, regional diversification can reduce product quality since long transit lead times may cause product degradation for perishable items as well as higher GHG emissions (Lim-Camacho et al., 2016; Ridoutt et al., 2016). regional diversification can also lower the risk of supply interruptions.

3.1 Mapping Supply Chains

Agriculture

Simple supply chain: Among the numerous stakeholders participating in the intricate networks that make up American agriculture supply chains are farmers, wholesalers, retailers, and consumers. To make these supply chains more climate change-resistant, the following simple structure may be developed:

1. **Sustainable farming techniques:** Encourage farmers to implement sustainable farming techniques that reduce greenhouse gas emissions, use less water, and enhance soil health. Agroforestry practices, reduced tillage, the development of cover crops, and the use of precision agriculture technologies can all contribute to this.

2. An efficient transportation system: Reducing the carbon footprint of agricultural supply networks is made possible by improved transportation efficiency. This can mean promoting the use of low-emission vehicles, condensing travel times by simplifying travel routes and reducing food waste by improving inventory management.

3. Climate-smart storage: to reduce post-harvest losses caused by climate change-related factors, such as severe weather, create climate-smart storage alternatives. Examples of ways to do this include using cold storage technology, introducing food preservation methods like canning and drying, and reducing food waste through improved inventory management.

4. Traceability and transparency: Increase traceability and transparency in agricultural supply chains to reduce the risk of food fraud and to ensure the quality and safety of agricultural products. This may entail passing legislation governing food safety, developing certification programs for sustainable farming practices, and utilizing blockchain technology to trace the movement of food products from farm to table.

5. **Educate consumers:** on the effects their dietary choices have on the environment and society. This might involve educating people on the environmental impact of various diets and agricultural methods, encouraging plant-based diets, and minimizing food waste through better meal preparation and storage techniques.

Complex supply chain: Several interconnected parts make up a complete supply chain structure for American agricultural products that is climate change resilient. Two broad categories may be used to arrange the framework:

1. Effective supply chain logistics: Reduce greenhouse gas emissions and post-harvest losses by organizing the storage and transportation of agricultural goods. Utilizing low-emission cars, streamlining transportation routes, creating climate-smart storage options, and enhancing inventory management through data-driven analytics and forecasting are some examples of how to do this.

2. Consumer education and behavior modification: Raise consumer knowledge of the environmental and social effects of their dietary decisions and promote behavior modification toward more environmentally friendly diets and the decrease of food waste. This can be accomplished through public awareness efforts, labeling and certification initiatives, and financial incentives for customers to select more environmentally friendly and sustainably sourced foods.
Overall, cooperation between farmers, suppliers, distributors, retailers, policymakers, and consumers is necessary to create an agricultural supply chain structure that is robust to climate change. We can build a more sustainable and resilient food system that is better able to respond to the challenges of climate change by cooperating to implement these interconnected components.

Food Processing

Supply Chain Framework: The following elements may be incorporated into a straightforward supply chain design for the food processing sector in America to make it climate change-resistant:

1. Encourage the adoption of sustainable procurement methods to minimize waste and cut down on the carbon footprint of raw materials. Using materials acquired locally, minimizing packaging waste, and using circular economy ideas are a few examples of how to achieve this.
2. Efficient manufacturing: Adopt energy-efficient technology, such as renewable energy sources, and put waste reduction methods into practice to increase energy efficiency and lower greenhouse gas emissions in food processing plants.
3. A climate-smart distribution: Distribute food items efficiently to cut down on waste and greenhouse gas emissions. To do this, you may employ data-driven inventory management, optimize your delivery routes, and use low-emission cars.
4. Transparency and traceability: By utilizing blockchain technology or other digital tracking techniques, the supply chain may be made more transparent and traceable. This can increase the effectiveness of the food supply chain, lower the possibility of food fraud, and guarantee the high quality and safety of food items.
5. Consumer education: Raise consumer understanding of how their food choices affect the environment and promote behavior change toward more sustainable diets and the decrease of food waste. This can be accomplished through public awareness efforts, labeling and certification initiatives, and financial incentives for customers to select more environmentally friendly and sustainably sourced foods.

The food processing industry in America may become more climate change resilient by putting these elements into practice, which will lessen the negative environmental effects of food production and delivery while preserving a sustainable food supply for future generations.

Mining

Supply Chain Framework

To address the issues brought on by climate change, the American mining sector may implement a crucial and robust supply chain structure. The following elements ought to be incorporated into the framework:

1. Promote environmentally friendly mining methods that limit water consumption, protect biodiversity, and reduce greenhouse gas emissions. This might involve utilizing energy-efficient equipment, cutting back on waste and pollution, and implementing top land restoration techniques. Some of the land restoration methods include soil stabilization, contouring, re-grading, revegetation, and erosion control.
2. Logistics and transportation improvements are needed to cut greenhouse gas emissions and make the most use of available resources. Utilizing low-emission cars, streamlining delivery routes, and putting data-driven inventory management into practice are a few examples of how to do this.
3. Risk management that is climate-smart: Create risk management plans that take into account how climate change may affect mining operations. This may entail investing in climate-resilient infrastructure as well as creating contingency plans for extreme weather conditions like floods or wildfires.
4. Transparency and traceability: Using digital monitoring techniques to monitor the movement of raw materials and completed goods will increase supply chain transparency and traceability. This can increase the effectiveness of the supply chain, lower the possibility of fraud, and guarantee that the minerals are sourced ethically.
5. Engagement with local communities and education are important for fostering trust, ensuring ethical mining methods, and advancing sustainable development. This may entail offering chances for education and training, carrying out analyses of the environmental and social impacts, and working with regional stakeholders on sustainability efforts.

The mining sector must cooperate with politicians, investors, and other stakeholders to identify and address the systemic difficulties brought on by climate change if this framework is to be implemented successfully. The mining sector can become more robust to the effects of climate change and contribute to a more sustainable future by implementing sustainable practices, enhancing logistics, controlling risk, increasing transparency, and interacting with communities.

IV. EMPIRICAL REVIEW

With the use of simulation, it has been determined how the structure of the supply chain and its disturbances affect the flow of products. Although the flow numbers utilized in our sample supply chain matrices include some uncertainty, they were most indicative of each situation. Information on the diamond supply chain was fairly hard to come by, maybe due to the security risks associated with revealing real values and routes. However, we have attempted to reduce problems related to parameterization uncertainty by concentrating on comparative studies compared to a baseline set of circumstances. Future research will be able to predict resilience using real connections, product quantities, and adaptive reactions by applying it to genuine commercial supply networks.

Additionally, it will be beneficial to add a degree of geographical analysis to supply chains that cross climatic zones so that risk at connections and nodes affected by a changing climate may be weighted and appraised appropriately. This study acknowledged that a wide range of additional factors, including the strength of relationships, information flow, inventory, the agility of individual organizations, and the perishability of a product, influence the resilience of chains in addition to the number of nodes, links, and volume of products. As a result, our method of estimating resilience only offers a first estimate; further research must include the effects of these additional factors on the flow of goods across supply chains as well as the intricate connections among those elements.

Because more time is spent on each relationship in a chain, simple supply chains, for instance, may have stronger ties between buyers and sellers. Such links are likely to affect the chain's agility and, consequently, any response to disruptive occurrences, along with the caliber of the information that is provided. Additionally, this study makes the false assumption that waste, such as increased transaction costs or time, is distributed equally across all linkages, which is seldom the case in real supply chains. In the future, fines might be imposed on links to represent such inefficiencies and test for effects on node criticality and, consequently, the chain's overall resilience. Therefore, depending on the caliber of the connections between nodes, the criticality of nodes may be increased or decreased.

Realistic assessment of the effects of climatic shocks on the chain is another area for development. We performed simulated 'knock-outs' at random, which presuppose impact on only one node. In reality, weather-related events may affect many nodes or may happen concurrently, affecting various links in the chain. Future simulations could weigh effects on a node based on how likely it is that a link would fail. This is because certain nodes are more durable than others; for instance, a big supplier's transport link is less likely to be compromised than a producer's transport link.

V. ETHICAL CONSIDERATIONS

All parties engaged must consider the moral implications of the complex interactions between economic, social, and environmental factors required to establish supply chain resilience to climate change. The following moral concerns must be taken into consideration when developing a framework for a supply chain that is climate change resilient:

Environmental Justice: Marginalized groups are disproportionately affected by the consequences of climate change because they typically lack the resources and resilience needed to cope with them. Therefore, it is essential to ensure that efforts to increase climate resilience do not exacerbate already-existing injustices and that the needs of those who are most vulnerable are given first attention.

Fair cost and benefit allocation: All parties engaging in climate resilience operations should equitably allocate the costs and rewards of their efforts. Making ensuring that everyone benefits equally from mitigation and adaptation measures while also dispersing their costs fairly along the supply chain is required for this.

Transparency and accountability: these are crucial for building confidence and ensuring that programs to promote climate resilience are morally sound and effective. Supply chain participants should be transparent about their sustainability initiatives and report on their progress toward climate resilience. They should also take responsibility for their actions and recognize any harm they may have done to the environment or society.

Respect for Human Rights: When developing climate resilience strategies, all stakeholders involved in the supply chain should have their human rights taken into account. This includes the right to a healthy environment, the right to a safe working environment, and the right to a fair salary.

Collaboration: When creating efforts to promote climate resilience, all stakeholders should be involved. Collaboration promotes shared accountability and helps to make sure that ethical concerns are included in the supply chain structure.

VI. CONCLUSION

For resource supply chains, climate change provides both hazards and possibilities, leading to global network reconfiguration. With the awareness that there is no simple definition of the optimality of supply chain topologies, this research offers a starting point for understanding the ramifications of interruptions on supply network architectures. The method utilized in this article offers a perspective that might help supply chains become more resilient and long-term sustainable by looking at them as a system of interactions and dependencies about adaptation goals. It supports the guiding concepts of adaptive co-management, a flexible strategy built on cooperation amongst several players who have a direct stake in natural systems (Armitage et al., 2008; Folke, 2006).

In the post-disruption recovery phase, this study emphasizes the significance of taking into account the larger economic benefits of varied chains, relating to risk reduction, business continuity, and enhanced system design. Proactive adaptation to strike a balance between the objectives of supply chain efficiency and cost reduction versus resilience and long-term sustainability will be crucial as climate change continues to raise unpredictability in the business and regulatory settings. Understanding risk's causes and anticipated manifestations are necessary for successful risk management. Without specifying the precise process, we have here simulated supply chain interruption due to climate change. The pressure on decision-makers to address these risks also grows as businesses become more aware of the rising danger of climate change's effects, especially in terms of corporate strategic direction and accountability. If this is not addressed, shareholders and other corporate stakeholders may be exposed to needless risk or lose out on opportunities, both of which may have legal repercussions.

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Appendix

Supply Chain	***No. Nodes* n.**	***No. Links* L**	***Links/Nodes* L/n**	***SCI Connectance Measure Standardized***	***Evenness (ED)***	***Resilience Score (1-SCI)***	***Key Elements 1***	***Key Elements 2***	***Key Elements 3***
Agriculture Simple (rice) pre-climate crisis	12	15	1.25	0.145	0.34	0.855	Lundberg Brown Rice	Texmati White Rice	Foreign Grown Rice
Agriculture Complex (rice) post-drought	20	25	1.25	0.071	0.20	0.929	Lundberg Brown Rice	Texmati White Rice	Grown Wild Rice
Food Processing Simple	22	33	1.5	0.048	0.26	0.952	(Processor) General Mills	Local Material Procurement	Exporters
Food Processing Simple	15	28	1.87	0.023	0.35	0.977	Wholesalers	Retailers/ Supermarkets	Shipping

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Mining simple	13	1	1.15	0.209	0.34	0.791	Conveyors	Onsite processors	Industrial sorting
Mining complex	16	23	1.43	0.044	0.52	0.944	Rail Corporation	Road/ conveyors	Sole use rail
Supply Chain	**No. Nodes n.**	**No. Links L**	**Links/Nodes L/n**	**SCI Connectance Measure Standardized**	**Evenness (ED)**	**Resilience Score (1-SCI)**	**Key Elements 1**	**Key Elements 2**	**Key Elements 3**
Agriculture Simple (rice) pre-climate crisis	12	15	1.25	0.145	0.34	0.855	Lundberg Brown Rice	Texmati White Rice	Foreign Grown Rice
Agriculture Complex (rice) post-drought	20	25	1.25	0.071	0.20	0.929	Lundberg Brown Rice	Texmati White Rice	Grown Wild Rice
Food Processing Simple	22	33	1.5	0.048	0.26	0.952	(Processor) General Mills	Local Material Procurement	Exporters
Food Processing Simple	15	28	1.87	0.023	0.35	0.977	Wholesalers	Retailers/ Supermarkets	Shipping
Mining simple	13	1	1.15	0.209	0.34	0.791	Conveyors	Onsite processors	Industrial sorting
Mining complex	16	23	1.43	0.044	0.52	0.944	Rail Corporation	Road/ conveyors	Sole use rail