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Evaluating the Vulnerability of Forestry Supply Chains Through Fuzzy Cognitive Map

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Abstract

It is crucial to address the significant role of the supply chain in economic activity and its vulnerable areas. This research focuses on the forestry industry, where obtaining and maintaining the primary raw material source is notably more challenging than other supply chains. The primary objective of this study is to analyze vulnerability factors specific to the forestry supply chain (FSC) by modeling their interactions and potential influences on each other. Initially, relevant factors were defined through a comprehensive literature review, encompassing vulnerabilities both in the general supply chain and pertinent to the forestry industry, such as natural disruptions. Then, the relationships between these factors were modeled and simulated using an input-sensitive fuzzy cognitive map (FCM). A cognitive map was constructed based on expert opinions, facilitated by triangular fuzzy numbers to express expert judgments accurately. FCM simulations using a new reasoning mechanism were conducted to analyze the effects of FSC vulnerability factors on one another across three sustainability-themed scenarios: economically related vulnerabilities, socially related vulnerabilities, and environmentally related vulnerabilities. Supply chain structure, government support, and source availability were the main vulnerability factors influencing the overall resilience of the FSC. Environmental stressors such as natural disturbances and climate change, and economic shocks, were found to significantly impact FSC dynamics, highlighting the need for adaptive strategies and robust contingency planning. This research is significant for stakeholders in the forestry industry as it elucidates the vulnerability factors within the FSC and demonstrates how different vulnerabilities can influence one another.

Keywords: Forestry supply chain, sustainable forestry, supply chain vulnerability, scenario analysis, triangular fuzzy numbers, fuzzy cognitive mapping.

1. Introduction

The forestry supply chain (FSC) encompasses the entire process of transforming raw materials from forests into finished wood and paper products, involving a complex network of stakeholders and activities from forest management and harvesting to the final distribution and consumption of forest products (Gavrilut et al., 2016; Scholz et al., 2018). FSCs integrate various operations, such as transportation, processing, storage, and logistics management, ensuring an efficient and sustainable flow of forest resources (Luo et al., 2021). Effective management of FSCs is essential for balancing economic development with environmental conservation, as forests play a vital role in providing ecosystem services such as carbon sequestration, biodiversity preservation, and water regulation (Wang and Tian, 2022). Optimizing FSC operations does not only improve the economic sustainability of forestry but also supports global trade, promotes economic growth in rural communities reliant on forest resources, and contributes to sustainable development goals by reducing environmental impacts (Chen et al., 2020; He and Turner, 2021).

However, FSCs face environmental, economic, and social challenges that complicate their management. From an environmental perspective, climate change modifies growth patterns (Lee et al., 2022), increases susceptibility to pests and diseases (Torresan et al., 2021), and intensifies the frequency and severity of natural disasters. Also, deforestation and degradation due to illegal logging and unsustainable harvesting practices contribute to biodiversity loss, soil erosion, and water depletion (Kumar et al., 2022). These environmental issues threaten the overall health of forests and their ecosystem services, undermining the long-terms sustainability of the forestry industry. On the economic front, FSCs are vulnerable to market fluctuations that cause price volatility for forest raw materials and products (Palander et al., 2024). High operational costs arise from transportation, labor, and regulatory compliance. Infrastructure constraints and trade barriers hinder efficient operations and market access, while

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investment risks introduce uncertainty for long-term forestry projects. Socially, FSCs encounter labor shortages, especially in remote and rural regions, as well as conflicts over land use and resource rights that can negatively affect local communities. Additional social challenges include health and safety risks, equity and access concerns regarding forest resources, and disruption to traditional lifestyles and cultural heritage due to changes in land use patterns.

Addressing these interconnected issues requires a comprehensive approach that balances environmental health, economic viability, and social equity in sustainable FSC management. Emerging trends and practices aim to mitigate these challenges. Erratic weather patterns, prolonged droughts, severe storms, and rising temperatures disrupt forest growth cycles, increase wildfire risks, and alter pest and disease dynamics (Seidl et al., 2017). In parallel, the loss of forest cover due to agricultural expansion, illegal logging, and urbanization diminishes forest resource availability (Curtis et al., 2018). In response, growing consumer awareness of deforestation and environmental degradation drives a major shift toward sustainable forestry practices, with certified wood products gaining preference. Demand for engineered wood products, such as cross-laminated timber, is increasing due to their superior strength, durability, and environmental benefits (Ramage et al., 2017). Moreover, the circular economy concept, which promotes the reuse, recycling, or repurposing of wood products, minimizes waste and encourages the sustainable use of resources (Korhonen et al., 2018). Effective monitoring of these trends is vital for ensuring a sustainable future for forest resources and the communities reliant on them.

Despite these positive trends, FSCs remain vulnerable to numerous disruptions that can compromise their ability to meet operational goals. Various factors, such as labor shortages, inefficient processes, policy failures, equipment malfunctions, natural hazards, pandemic outbreaks, power outages, and economic crises, can impede the smooth flow of products and services along the supply chain (Pandit et al., 2021). The complexity and interdependence of the various stages of FSCs make them particularly vulnerable to these risks. When vulnerabilities in supply chains are unaddressed, operational efficiency can be compromised, leading to delays, increased costs, and resource waste. These inefficiencies hinder the effectiveness of FSCs in meeting market demands and maintaining a steady supply. Additionally, vulnerabilities threaten the sustainability of FSCs by exacerbating environmental degradation, reducing the resilience of forest ecosystems, and hindering the implementation of sustainable management practices.

Beyond these broader insights on supply chains, FSCs are significantly influenced by advanced technologies and Industry 4.0 (He and Turner, 2021). Forest biomass utilization is key to renewable energy production and product development (Zhang et al., 2020). Transportation plays a critical role in reducing CO2 emissions, with the choice of road, rail, or waterway, depending on distance and cost considerations (Wolfsmayr and Rauch, 2014). Consequently, managing risks within FSCs is essential for maintaining competitive advantages and promoting sustainable forestry (Wang et al., 2023). The mobilization levels of FSCs vary widely across countries, influenced by policy, market, and technological factors (Thiffault et al., 2016). Natural disruptions, including storms, wildfires, and insect infestations, also impact timber supply and properties, posing significant challenges (Roos, 2023). Furthermore, adopting digital technologies and Industry 4.0 concepts in the forest sector, often called Forestry 4.0, has optimized FSC operations (Feng and Audy, 2021). Establishing forest-based bio-refineries for bio-energy production offers potential for new revenue streams and environmental benefits (Cambero and Sowlati, 2016).

In recent studies, researchers have focused on addressing specific supplychain challenges. For instance, Elias et al. (2021) conducted a holistic analysis of the complex interactions among barriers affecting the adoption of sustainable wood supply chain management, identifying bureaucracy, regulatory requirements, and distribution challenges as the most significant obstacles. Sharma et al. (2024; 2023) examined factors causing vulnerability in manufacturing supply chains. They distinguished between supply chain risk and vulnerability, identifying supply chain complexity as the most significant factor. They also highlighted key influencing factors such as “risk not being a boardroom agenda,” “nonalignment of performance measures and rewards,” and “lack of a risk dashboard.” Their integrative model linking these factors underscores the need to address factor interactions, a gap our study fills using a Fuzzy Cognitive Map (FCM). Similarly, Roos (2023) reviewed the impact of forest damage caused by biophysical factors, such as insect infestation, wildfires, climate change, and storms, on FSCs and how to manage these disturbances. They found that climate change is the underlying cause of supply disruptions. Wang et al. (2023) focused on supply chain risks in the forestry industry as an obstacle to sustainable forestry, categorizing risks into supply/source, manufacturing, logistic/transport, demand/market, and environmental risks. Lanfredi et al. (2023) analyzed the outcomes of increased woodland areas, which were perceived as beneficial but incompatible with sectoral policies. They concluded that this expansion increases vulnerability to wildfires and other forms of degradation, resulting in economic and quality losses.

Supply chain vulnerability is a critical aspect of risk management and is closely related to resilience (Elleuch et al., 2016; Gomes, 2022). Resilience, flexibility, and agility are interconnected with vulnerability, with resilience playing a pivotal role in mitigating it (Liu et al., 2015; Radhakrishnan et al., 2018). Evaluating supply chain vulnerability is essential for developing strategies to reduce risks and strengthen resilience (Deshpande et al., 2023; Sharma et al., 2022). Supply chain vulnerability stems from decisions that heighten exposure to potential disruptions, acting as a precursor to supply chain risks (Ivanov and Sokolov, 2019). Rather than focusing solely on specific disruptive events, vulnerability underscores susceptibility to these disruptions and their impact on economic viability (Dechprom and Jermsittiparsert, 2019; Mensah et al., 2015). Structuring supply chain vulnerability into measurable criteria enables managers to identify clear starting points for mitigation. It is crucial to assign specific weights to each criterion to pinpoint the most critical factors and enable a focused strategy to reduce supply chain vulnerability (Sharma et al., 2023).

Despite extensive research on supply chain vulnerability, notable gaps remain in understanding and addressing the relationships between vulnerability factors in FSCs. Many studies tend to isolate specific aspects that can hinder effective vulnerability management. For example, Wolfsmayr and Rauch (2014) argue for more integrated approaches within forest fuel supply chains, emphasizing that neglecting the interconnectedness of various elements can hinder effective vulnerability management. Acuna et al. (2019) emphize addressing risks across all supply chain segments, especially in sustainable biomass production. Dashtpeyma and Ghodsi (2021) highlight gaps in integrating economic, environmental, and social factors, while He and Turner (2021) note the fragmented adoption of digitization and Industry 4.0, leaving vulnerabilities unaddressed. Roos (2023) identifies the need for better integrating biophysical disruptions (i.e., wildfires) into broader assessments. These studies emphasize the need for comprehensive methodologies that address the diverse factors contributing to FSC vulnerabilities. Also, exploring their dynamic nature under changing environmental and technological conditions underscores the importance of a holistic approach that offers actionable insights for supply chain managers.

There has been a growing interest in leveraging advanced methodologies to address the complexities of supply chain management, particularly in enhancing resilience and mitigating risks. This context would set the stage for discussing the role of FCMs in this context. FCMs have been used to enhance supply chain resilience by analyzing the interrelationships between key variables that influence resilience (Sabahi and Stanfield, 2019). Soyer et al. (2023) proposed a hesitant approach to classical FCM to examine sustainable supply chain risks and their impact on performance, demonstrating FCM's capability to capture uncertainty in complex systems. A literature review reveals a growing number of publications using FCMs, particularly for multi-criterion decision-making (MCDM) support, underlining FCM's relevance in supply chain decision-making (Zanon and Carpinetti, 2018). Additionally, FCM methodology has been employed to understand relationships among supply chain integration, strategies, risk factors, and performance criteria in an automobile manufacturer, demonstrating its effectiveness in considering interrelations between criteria in supply chain management (Dursun et al., 2019).

There is a limited application of advanced analytical tools, such as FCMs, for modeling and analyzing the intricate web of interactions among vulnerability factors in FSC. FCM offers several advantages that justify its use in assessing vulnerabilities in FSCs. First, FCM provides a systematic framework for modeling complex systems by capturing the causal relationships and feedback loops among various factors influencing FSCs (Özesmi and Özesmi, 2004). Unlike traditional modeling approaches, FCM can accommodate uncertainty and fuzziness in data, making it suitable for the dynamic and interconnected nature of FSCs where precise quantitative data may be limited or uncertain (Papageorgiou and Salmeron, 2013). FCM generates a visual map of causal relationships between factors influencing FSC vulnerability. This visual representation enhances the understanding and communication of the complex dynamics, making the findings more accessible to stakeholders. Fuzzy logic, a mathematical approach that deals with uncertainty and vagueness, has also been underutilized in FSC vulnerability assessments. This study demonstrates the potential of FCM, incorporating fuzzy logic, to model the uncertainties and ambiguities inherent in such assessments. These gaps underscore the motivation of this study: to provide a holistic assessment of FSC vulnerabilities using FCM. This approach bridges existing knowledge gaps, offers new insights into the interdependencies among FSCs, and informs strategies for improving their resilience and sustainability.

The main research objectives of this study are as follows:

- To identify and categorize key vulnerabilities affecting FSCs.
- To develop an FCM model representing causal relationships and interdependencies among these vulnerability factors.
- To contribute to the existing knowledge on FSCs by providing a comprehensive and integrated assessment of vulnerabilities using an advanced analytical tool like FCM.

2. Material and Methods

This study used a decision-making approach to reveal the factors associated with FSC vulnerability using FCM based on expert opinions enhanced with triangular fuzzy numbers (TFNs). The approach was implemented as described below (Figure 1):

- Step 1. Engage experts to determine and evaluate factors.

- Step 2. Determine the factors causing FSC vulnerability.
- Step 3: Request experts to evaluate factors. Experts are encouraged to use the linguistic terms in Table 1 to assess relationship magnitude and specify direction as "positive" or "negative." The linguistic scale in the table is adapted and simplified from the work of Sun (2010).
- Step 4. Aggregate the individual evaluations to acquire a single fuzzy evaluation matrix.
- Step 5. Defuzzify the evaluation matrix to transform the fuzzy evaluation matrix into a crips evaluation matrix.
- Step 6. Perform FCM simulations to analyze vulnerability-driving situations across various scenarios.

Figure 1. An overview of the steps involved in the proposed approach

Table 1. Linguistic terms to evaluate relationships

Linguistic term	Triangular fuzzy number (l, m, u)
High	(0.7, 0.8, 0,9)
Medium	(0.4, 0.5, 0.6)
Low	(0.1, 0.2, 0.3)

2.1. Preliminaries of Triangular Fuzzy Numbers

This section briefly reviews some basic definitions of fuzzy sets and numbers used throughout this paper unless otherwise noted. A fuzzy set $\tilde{A}$ is defined by a membership function $\mu_{\tilde{A}}(x)$, which assigns a real number within the range of [0, 1] to each element x in the universe of discourse X. A fuzzy set $\tilde{A}$ is convex if and only if inequality (Equation 1) holds for all x_1, x_2 in X and $\lambda \in [0,1]$ (Yesil et al., 2014).

$$\mu_{\tilde{A}}(\lambda x_1 + (1-\lambda)x_2) \geq \mathrm{Min}\big(\mu_{\tilde{A}}(x_1), \mu_{\tilde{A}}(x_2)\big) \quad (1)$$

A fuzzy number is a fuzzy subset of X that is characterized by being both convex and normal. According to fuzzy set theory, classical sets are encompassed within a broader category of fuzzy sets; thus, crisp numbers are a specific instance of fuzzy numbers because they share all the same properties. A crisp number $\mathbb{x}$ can be represented by a fuzzy number $\tilde{p}$ defined by the membership function in Equation 2. Crisp numbers that are interpreted as fuzzy numbers are commonly referred to as fuzzy singletons.

$$\mu_{\tilde{p}}(x) = \begin{cases} 0, & x < \mathbb{x} \\ 1, & x = \mathbb{x} \\ 0, & x > \mathbb{x} \end{cases} \quad (2)$$

A triangular fuzzy number (TFN) $\tilde{a}$ can be described by a triplet (a^L, a^M, a^U). The membership function $\mu_{\tilde{a}}(x)$ is defined as given in Equation 3 (van Laarhoven and Pedrycz, 1983):

$$\mu_{\tilde{a}}(x) = \begin{cases} 0, & x < a^L \\ \frac{x-a^L}{a^M-a^L}, & a^L \leq x \leq a^M \\ \frac{x-a^U}{a^M-a^U}, & a^M \leq x \leq a^U \\ 0, & x \geq a^U \end{cases} \quad (3)$$

where $a^L \leq a^M \leq a^U$, with a^L and a^U representing the lower and upper bounds of the support of $\tilde{a}$, respectively, and a^M denoting the modal value.

The basic mathematical operations of summation, multiplication, and scalar multiplication related to positive TFNs, $\tilde{a}$ and $\tilde{b}$, are given by Equations 4, 5, and 6, respectively.

$$\tilde{a} \oplus \tilde{b} = (a^L, a^M, a^U) \oplus (b^L, b^M, b^U) = (a^L + b^L, a^M + b^M, a^U + b^U) \quad (4)$$

$$\tilde{a} \otimes \tilde{b} = (a^L, a^M, a^U) \otimes (b^L, b^M, b^U) = (a^L b^L, a^M b^M, a^U b^U) \quad (5)$$

$$\lambda \otimes \tilde{a} = \lambda \otimes (a^L, a^M, a^U) = (\lambda a^L, \lambda a^M, \lambda a^U), \lambda > 0 \quad (6)$$

2.2. Fuzzy Cognitive Map

Fuzzy Cognitive Map (FCM) is a soft computing tool that enables the creation of a structural model of interactions among system concepts and modeling the consequences of these interactions on the system. FCM was introduced into the literature by Kosko (1986), who further developed cognitive maps by quantifying interactions and system concepts to address system dynamics. FCM allows individuals to visually present the relationships they intuitively know exist between system concepts (Podvesovskii and Isaev, 2018). The fundamental building keystone of an FCM is a map composed of nodes representing the system's concepts and edges depicting interactions among these concepts. This map transforms the conceptual understanding of system concepts and their relationships into a visual representation. A mathematical depiction of the FCM model is also necessary to concretize the system dynamics resulting from these interactions.

For a system with n different concepts, a concept is represented by C_i, $i = 1,2,\ldots,n$. The attribute represented by the C_i node is quantified by numerical value A_i, $i = 1,2,\ldots,n$, which denotes its activation level. The A_i values typically range between [0,1]; where 0 indicates that the attribute is completely inactive, 1 indicates that the attribute is fully active, and other values denote partial activation (Papageorgiou and Salmeron, 2013). The degrees to which C_i concept influence others, i.e., causal relationships are denoted by w_{ij}, $i = 1,2,\ldots,n$ and $j = 1,2,\ldots,n$.

To model the behavior of the system, it is necessary to mathematically depict the map through its matrix representation, as shown in Equation 9. This matrix is referred to as the adjacency matrix.

$$W = \begin{bmatrix} w_{11} & \cdots & w_{1n} \\ \cdots & w_{ij} & \cdots \\ w_{n1} & \cdots & w_{nn} \end{bmatrix} \quad (9)$$

In the classical approach, the causal relationships in the matrix take values within the range [-1,1], and it is assumed that a system concept does not have an effect on itself, i.e., $w_{ii} = 0$ (Parsopoulos et al., 2003). A positive w_{ij} value signifies a causal increase, meaning that when A_i increases, A_j also increases, and vice versa. A negative w_{ij} signifies a causal decrease, meaning that when A_i increases, A_j decreases, and vice versa. If there is no causal relationship between A_i and A_j, then $w_{ij} = 0$.

Dynamic analysis using FCM is feasible through simulations that execute these causal relationships. Thus, by examining the activation levels of all concepts at a given time t, the state of the system can be represented as $\boldsymbol{A}^t = [{A_1}^t, {A_2}^t, \ldots {A_n}^t]$. During the simulation, the activation value of concept C_i at time t, A_i, is determined as shown in Equation 10.

$${A_i}^t = f\left({A_i}^{t-1} + \sum_{\substack{j=1 \\ j\neq i}}^{n} w_{ji} * {A_j}^t\right) \quad (10)$$

Here, ${A_i}^{t-1}$ is the activation value of concept C_i at the previous step, and w_{ij} is the magnitude of the causal relationship between concept C_j and concept C_i. In summary, the activation level of C_i at time t is determined by applying a threshold function f to the sum of its current activation level and the change induced by other concepts. f normalizes the values of the concepts to a particular range at each step to facilitate comparisons among the concepts. The sigmoid and hyperbolic sigmoid functions are commonly used threshold functions (Bueno and Salmeron, 2009).

After sufficient iterations, the long-term behavior of the system can be obtained. These behaviors typically include convergence to a fixed point, cycle, or chaotic behavior. Repeated simulations from initial states A_0 allow for the interpretation of the effects of initial states based on the resulting states of the simulation (Papageorgiou and Salmeron, 2013).

However, FCM has been criticized for producing the same final vector regardless of changes in the initial state vectors. Asan and Kadaifçi (2020) propose an approach for obtaining the final vector through a reasoning mechanism that accounts for both direct and indirect relationships, in contrast to the classical FCM, which only considers direct relationships during simulation. This study extends the reachability matrix calculation method introduced by Asan and Kadaifçi (2020). The reachability matrix calculation is further developed as shown in Equation 11. The proposed approach normalizes the matrices, which have been raised to their respective powers, according to the maximum weight ${w_{max}}^k$ in W^k and then sums the normalized matrices.

$$\mathfrak{R} = \sum_{k=1}^{n} \omega^k \quad (11)$$

where ω^k is the normalized form of W^k, as specified in Equation 12:

$$\omega^k = \frac{W^k}{{w_{max}}^k} \quad (12)$$

It continues by simulating the system starting from an initial state, by multiplying the initial state A_0 and $\mathfrak{R}$. Thus, the final state of the system is acquired as $A_0 \times \mathfrak{R}$. To interpret this final state vector, a final step that involves normalizing this vector by its maximum value is performed. Equation 13 gives the normalized final state vector. This revised calculation provides the final state based on a one-step simulation to draw inferences on the system's behavior originating from a specific initial state.

$$A_f = {A_0 \times \mathfrak{R}} \Big/ {\max(A_0 \times \mathfrak{R})} \quad (13)$$

2.3. Application

The application section of this study focuses on the complexities of FSC by identifying critical vulnerability factors through a rigorous literature review. This study employs FCM as a robust analytical tool by recognizing the interconnected nature of these factors and their potential for diverse impacts. FCM is instrumental in visualizing and quantifying the intricate relationships among these vulnerabilities and their subsequent effects on the FSC system.

2.4. Determining Criteria Set

The literature review identified the factors in Table 2 as the causal areas of vulnerability. It has been established that FSC operates in a complex and dynamic environment influenced by several interconnected factors. These factors can be categorized into environmental, economic, social, and operational dimensions.

Table 2. Factors causing vulnerability in FSC

Factor Category	Factors	Source
Environmental	Natural disturbance (C1)	(Roos, 2023; Yang and Liu, 2018)
	Climate change (C2)	(Roos, 2023)
Economic	Market demand (C3)	(Yang and Liu, 2018)
	Economic downturns (C4)	(Liu and Ning, 2023)
Social	Workforce availability (C5)	(Hoffmann et al., 2018)
	Community acceptance (C6)	(Barnett, 2018)
Operational	Technological advancement (C7)	(Pandirwar et al., 2023)
	Environmental regulations (C8)	(Garrett et al., 2021)
	Trade policies (C9)	(Zhang et al., 2021)
	Resource availability (C10)	(Wang et al., 2023)
	Contingency planning awareness (C11)	Expert view
	Government support (C12)	(Vermeulen and Kok, 2012)
	Collaboration (C13)	(Sharma et al., 2023)
	Supply chain structure convenience (C14)	(Greenslade et al., 2021)

2.4.1. Environmental Factors

Natural disturbances (C1): Wildfires, insect infestations, and extreme weather events can significantly disrupt forest ecosystems, leading to timber shortages, infrastructure damage, and increased harvesting costs. For instance, large-scale wildfires can destroy vast areas of forests, reducing timber availability for years and disrupting transportation routes. Climate change (C2): Rising temperatures, changing rainfall patterns, and increased frequency of extreme weather events pose long-term threats to forest health and productivity. These can result in reduced timber growth, increased pest and disease outbreaks, and altered forest composition, affecting overall supply chain stability.

2.4.2. Economic Factors

Market demand (C3): Fluctuations in demand for forest products driven by economic cycles, construction activity, and consumer preferences can lead to price volatility, overstocking, and shortages. Sudden increases in demand may strain resources and lead to bottlenecks, whereas decreases can result in reduced revenues and potential closures. Economic downturns (C4): Recessions and economic crises can significantly impact the forestry industry. Decreased consumer spending reduces demand for forest products, lower timber prices, and potential job losses throughout the supply chain. In addition, financial constraints may limit forest management and infrastructure investments.

2.4.3. Social Factors

Workforce availability (C5): Shortages in skilled labor, particularly in specialized areas (i.e., forestry and logging), can hinder operations, increase costs, and impact the overall efficiency of the supply chain. Aging workforces and competition from other industries can intensify this issue. Community acceptance (C6): Social conflicts, environmental concerns, and perceptions of the industry’s impact on local communities can create challenges for forest operations. Maintaining a positive social license to operate is essential to secure long-term access to resources and minimize disruptions.

2.4.4. Operational Factors

Technological advancements (C7): Adopting new technologies can enhance efficiency, reduce costs, and improve sustainability, but it also requires significant investments and workforce training. The pace of technological change can create challenges for smaller companies with limited resources. Environmental regulations (C8): Compliance with environmental regulations is essential for sustainable operations, but it can increase costs and operational complexity. Stringent regulations may restrict forest resources access and require investments in pollution control and monitoring technologies. Trade policies (C9): Tariffs, quotas, and trade agreements significantly impact market access, prices, and competition for forest products. Changes in trade policies can create uncertainty and require adjustments to supply chain strategies. Resource availability (C10): Limited access to forest resources due to land-use changes, competition from other sectors, and depletion can constrain production and increase costs. Fluctuations in timber quality and quantity can also affect product quality and processing efficiency. Contingency planning awareness (C11): Developing and implementing effective contingency plans to address potential disruptions, such as natural disasters, supply chain breakdowns, or economic shocks, is crucial for business continuity and resilience. Government support (C12): Government policies, regulations, and financial incentives significantly influence the forestry industry's competitiveness and sustainability. Supportive policies can facilitate investments, promote innovation, and create a favorable business environment. Collaboration (C13): Effective collaboration among forest landowners, loggers, processors, and other supply chain partners can improve efficiency, reduce costs, and enhance overall performance. Information sharing, joint planning, and risk management can mitigate disruptions and strengthen supply chains. Supply chain structure convenience (C14): The complexity of a supply chain, including the number of intermediaries, transportation distances, and inventory levels, influences its vulnerability to disruptions. A highly complex and interconnected supply chain may be more susceptible to shocks than a simpler, more integrated structure. Understanding the interplay among these factors is crucial for developing resilient FSCs. In addition, industry stakeholders can enhance long-term sustainability and profitability by proactively identifying and addressing potential challenges.

2.5. Building FCM

After determining the factors associated with FSC vulnerability, four domain experts were engaged in constructing the FCM model by evaluating the relationships between them. All experts are knowledgeable about forestry and the supply chain. Employing the structured linguistic scale in Table 1, the experts qualitatively assessed the strength and direction of these relationships.

Table 3. Relationships between the FSC vulnerability factors

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14
C1		0.094		0.138						-0.469	0.138			
C2	0.275									-0.319				
C3		0.063		0.106		0.063				-0.244		0.213		
C4			-0.650		-0.031		-0.138	0.138	-0.138	0.213				-0.213
C5										0.213			0.319	
C6			0.213		0.319							0.138	0.169	
C7					0.256				0.063					0.425
C8	-0.169	-0.244							0.138	0.063	0.138			0.138
C9			0.319	-0.213						0.138			0.138	
C10	0.213													
C11						0.063		0.213						
C12			0.244		0.213		0.288	0.394	0.319	0.138	0.244			
C13						0.094					0.063			0.575
C14							0.275		0.288				0.394	

The qualitative expert judgments were then transformed into quantifiable data using TFNs, enabling the subsequent aggregation of multiple expert opinions using Equation 1 into a consolidated relationship matrix. Relationships with two or more expert opinions were directly incorporated into the matrix, whereas solitary opinions were considered negligible. The aggregated matrix was subsequently defuzzified using Equation 8 and transformed into the crisp relationship matrix shown in Table 3, thereby facilitating a clearer representation of factor interactions. The derived relationship matrix in Table 3 is the foundation for constructing the map shown in Figure 2.

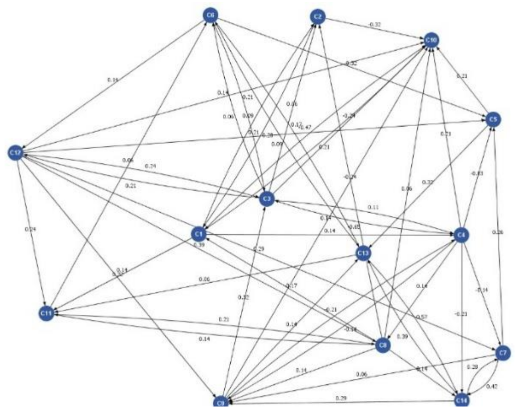

Figure 2. FCM model for FSC vulnerability

3. Results and Discussion

The map in Figure 2 graphically depicts the intricate connections among the vulnerability factors within the FSC. According to the map, the most central factor, with a centrality value of 2.306, indicating the sum of the absolute magnitudes of its direct interactions, is the convenience of the Supply Chain Structure (C14). This finding aligns with previous studies that emphasize the importance of a well-structured supply chain in mitigating vulnerabilities (He and Turner, 2021; Ivanov, 2017). Government support (C12), market demand (C3), and source availability (C10) are, respectively, the following most central factors. These are significantly influenced by or have a substantial impact on others through their associated interactions. Dubey et al. (2023) highlighted how government interventions can shape market dynamics and supply chain effectiveness. The factor most influenced and altered by other factors is Source Availability (C10), with an in-degree value of 1.794, indicating the sum of the absolute magnitudes of the relationships affecting it. It means that any change in FSC could significantly impact the raw material sources that sustain the system. Raulier et al. (2014) expressed concern regarding the impact of natural disruptions on timber supply. It reinforces the need for effective risk management strategies that address the vulnerabilities of resource availability in FSCs (Jüttner et al., 2003). The otherfactors with high centrality values are market demand (C3) and Supply Chain Structure (C14). Finally, Government support (C12) and Economic downturns (C4), with out-degree values of 1.837 and 1.519 respectively, which is the opposite of in-degree, are the factors with the highest potential to cause changes in the FSC system dynamics. This observation is consistent with findings from Pettit et al. (2019), who argued that government policies and economic conditions are pivotal in shaping the resilience and adaptability of supply chains.

To understand the dynamic behavior of the FSC under varying conditions, analyses were conducted based on the simulation of cause–effect relationships in the map using Equation 13. A sustainability-centric approach was adopted, with three distinct scenarios formulated, each targeting a specific sustainability dimension. Each scenario is characterized by a unique initial state vector encompassing actions relevant to its sustainability objectives.

The first scenario, which considers environmental impacts, was initialized with an initial state vector of [1,1,0,0,0,0,0,0,0,0,0,0,0,0]. This scenario assumes that initially, only the factors of natural disturbance (C1) and climate change (C2) are active, meaning that FSC is vulnerable to only these two factors. Therefore, by simulating the system under the influence of these two factors, changes in the FSC dynamics, including environmental factors and others, were observed. Accordingly, FSC dynamics with direct and indirect relationships directed the system to a state of [0.792, 0.860, 0.316, 1.000, 0.571, 0.700, 0.426, 0.793, 0.376, 0.000, 0.850, 0.638, 0.225, 0.082]. The system behavior in terms of the initial and final states is illustrated in Figure 3(a).

The initial state vector for the second scenario, focusing on economic factors, was set to [0,0,1,1,0,0,0,0,0,0,0,0,0,0] to determine how economic-oriented vulnerabilities impact other vulnerability-causing factors in FSC. Such an initial state triggers most sources in the FSC, as indicated by the final state vector [0.921, 0.881, 0.333, 1.000, 0.646, 0.777, 0.461, 0.872, 0.398, 0.954, 0.806, 0.765, 0.186, 0.000], except for a few. For instance, while changes in demand that support the flow within the supply chain can encourage the enrichment of resources for the forestry industry, economic slowdowns may cause forest areas to shrink as investors redirect their resources to more profitable ventures. It is also clear from Figure 3(b) that Demand-driven vulnerabilities have a weaker impact when other vulnerabilities come into play.

Finally, the third scenario addresses vulnerabilities related to social factors. Here, the initial state vector was set to [0,0,0,0,1,1,0,0,0,0,0,0,0,0]. The result of this scenario, [0.082, 0.075, 0.487, 0.000, 0.383, 0.232, 0.502, 0.199, 0.582, 0.175, 0.229, 0.245, 0.9, 1.000], social vulnerabilities, except for two factors, do not show high potential for causing vulnerabilities in other factors as seen in Figure 3(c). Due to the direct correlation of workforce availability (C5) and community acceptance (C6) with the adoption of FSC activities, their vulnerabilities can only trigger vulnerabilities within the supply chain structure convenience (C14), and collaboration (C13).

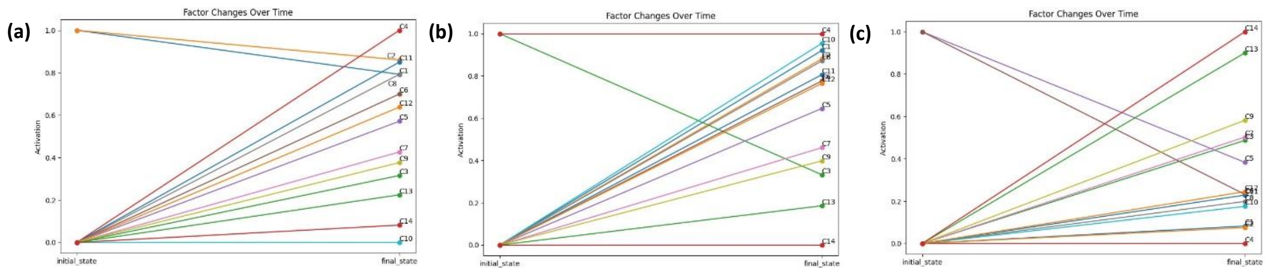

Figure 3. Emerging of vulnerability causing factors in terms of scenarios

By simulating each scenario using its corresponding initial state vector, this study explored the potential trajectories of the FSC system under different conditions. The resulting system states provide valuable insights into the vulnerabilities that may emerge and their potential impacts on the FSC's overall performance and resilience.

4. Conclusion

FSC plays a significant role in sustainable forest management and global economic stability. However, its complex and interconnected nature exposes it to various vulnerabilities, ranging from environmental disruptions to economic fluctuations and social challenges. This study employed FCM as a novel approach to comprehensively assess these vulnerabilities.

This study identified key factors affecting FSC vulnerability across environmental, economic, social, and operational dimensions through a detailed review and analysis. Factors such as climate change, market demand volatility, workforce shortages, and regulatory complexities emerged as critical influencers. FCM provided a structured framework to model the intricate relationships and feedback loops among these factors, offering insights into their combined impacts on FSC resilience.

The application of FCM highlighted the centrality of factors, including supply chain structure, government support, and resource availability, in shaping FSC dynamics. Visualizing these interdependencies allows administrators to understand better and prioritize strategies to mitigate risks and enhance sustainability. The simulation scenarios underscore the sensitivity of FSCs to environmental stressors and economic shocks, emphasizing the need for adaptive strategies and robust contingency planning.

Furthermore, this study identified gaps in current research, particularly in integrating diverse vulnerability factors and leveraging advanced analytical tools like FCM with the ease of evaluation offered to experts with the help of TFNs. A key limitation of this study is the lack of a comprehensive sensitivity analysis that considers how the qualifications and backgrounds of various expert groups may influence the assessment of factors in forest sector supply chains. Specifically, the study does not account for the differing perspectives of sectors such as environmental activists, industry professionals, or policymakers. It does not compare the impact of different forest management systems on factor weightings, like state-managed versus privately managed forestry.

Future research should address these gaps by conducting a thorough sensitivity analysis to evaluate how diverse expert opinions might affect factor assessments and potentially alter results. Additionally, comparative studies are needed to examine the influence of different forest management systems on these weightings, offering more profound insights into how management practices affect vulnerability assessments. Expanding research in these areas would enhance the model's robustness and versatility for decision-makers across various forestry contexts.

In conclusion, comprehending FSC vulnerability requires a holistic approach that addresses environmental sustainability, economic stability, and social equity. By adopting innovative methodologies such as FCM, stakeholders can navigate uncertainties, foster sustainable practices, and ensure the long-term viability of forest resources and communities that depend on them.

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