Community-informed Decisions for Equitable, Cost-effective, and Inclusive Disaster Resilience Planning (Co-DECIDR): A modeling approach

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Abstract
Evaluating coping strategies for community resilience planning in the face of natural hazards and disasters presents significant challenges, including limited system clarity, diverging community priorities, resource inequalities, and inherent uncertainties. Traditional methods — often reliant on economic metrics through benefit-cost analysis — primarily assess monetary aspects, overlooking critical non-monetary factors. The increasing shift towards transdisciplinary methods underscores the importance of integrating local community values into resilience planning. This research introduces the Co-DECIDR (Community-informed Decisions for Equitable, Cost-effective, and Inclusive Disaster Resilience) modeling framework, designed to evaluate resilience planning alternatives by embracing community-identified values, leveraging local insights, navigating uncertainties, and balancing monetary with non-monetary considerations. By merging Fuzzy Cognitive Mapping (FCM) for qualitative depth with Benefit-Cost Analysis (BCA) for quantitative rigor, Co-DECIDR enables a comprehensive understanding of complex social-ecological systems. The framework utilizes accessible online tools — Mental Modeler for FCM and Economic Decision Guide Software (EDGe$) for BCA — to enhance user engagement and model efficacy. Demonstrated through proof-of-concept examples in Flint, Michigan, focusing on resilience to extreme weather events and pandemics like COVID-19, this study showcases Co-DECIDR's practicality and adaptability in real-world contexts. These examples highlight the framework's capacity to support informed, community-centric, and equitable resilience planning. Furthermore, Co-DECIDR advances good modeling practice by utilizing participatory modeling in resilience planning to bridge the gap between modelers and end-users. It systematically captures stakeholder requirements, investigates subjectivity, addresses collaborative modeling challenges, encourages the engagement of diverse groups, and adopts a comprehensive approach to assessing model performance, embracing both qualitative and quantitative criteria.

Keywords
community resilience; social-ecological systems; participatory modeling; fuzzy cognitive mapping; benefit-cost analysis

Code availability
All modeling tools employed in this study are accessible to the public online. The input data utilized for the proof-of-concept examples can be found in the Supplementary Material.

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1. Introduction

The importance of resilience planning in the context of socio-environmental systems (SES) has gained considerable attention recently, as this type of systems thinking can enhance the ability of communities to adapt to, build resilience towards, and recover from a wide range of acute challenges as well as persistent environmental and social stressors (Jaramillo et al., 2021; Lambrou & Loukaitou-Sideris, 2022). Resilience planning can be defined as a process in which possible risks and hazards are pinpointed, and subsequently, strategies for adaptation, mitigation, and recovery are developed (McAllister et al., 2015). These efforts aim to create more resilient SES that can better withstand shocks and ensure the continued well-being of community members, socio-economic functions, and ecosystem stability. Yet, resilience planning in the context of complex adaptive systems (Levin et al., 2013), such as SES, entails multiple challenges. Primarily, a notable lack of clear definitions for resilience indicators, trade-offs among different resilience goals and community-identified values, and the uncertainty and complexity of socio-environmental dynamics (Sellberg et al., 2018; Helgeson & O'Fallon, 2021; Jaramillo et al., 2021; Chollett et al., 2022; Gu et al., 2023). As a result, resilience planning for SES requires a comprehensive and interdisciplinary approach that considers the intertwined interactions of multiple human and natural subsystems within and across various temporal and spatial scales, while addressing the substantial uncertainties inherent in these systems (Sellberg et al., 2018). Moreover, it is essential for resilience planning to foster effective collaboration among diverse stakeholder groups and community members to ensure the selection of equitable and effective interventions (Bostick et al., 2017; Neely et al., 2021).

The approach presented in this paper emphasizes integrating Good Modeling Practices (GMP) in modeling to support resilience planning. It extends beyond merely recognizing challenges to actively formulating and implementing a framework that is both robust and inclusive. This shift is crucial in addressing the complex dynamics of SES and ensuring that resilience strategies are effective, equitable, and aligned with the diverse values and needs of communities. (Koliou et al., 2020; Van de Lindt et al., 2023). Several key principles have been identified as 'good practices' for modeling SES, including the use of interdisciplinary approaches and stakeholder engagement, rigorous identification, quantification, and communication of uncertainty in model development, transparency in model design and execution, and the careful comparison and justification of methodological tools selected for model development (Jakeman et al., 2006; Guillaume et al., 2017; Jakeman et al., 2018). Addressing the previously mentioned challenges in resilience planning requires a modeling approach that combines both qualitative and quantitative methods. This approach should not only consider the inherent uncertainty in model input data and output information—facilitating improved decision-making under conditions of uncertainty—but also account for the intricate interrelationships and feedback loops among the system's components. Additionally, this approach must harness transdisciplinary methods to actively engage a diverse range of stakeholders with varying perspectives to ensure the model's comprehensiveness and relevance (Koliou et al., 2020).

In this study, we introduce the Community-informed Decisions for Equitable, Cost-effective, and Inclusive Disaster Resilience (Co-DECIDR) modeling approach, tailored for community-based resilience planning within SES. Co-DECIDR is grounded in GMP, designed to enhance decision-making by incorporating trade-off analysis and considering the complex interplay between physical infrastructure, social institutions, and natural ecosystems. In the domain of resilience planning, choosing the suitable modeling technique is crucial. Economic modeling techniques (such as input-output models) offer simplicity and ease of use for policy assessment, but often at the expense of nuance and comprehensiveness. These methods typically rely on single-point estimates and may not fully capture non-market values, community preferences, or the uncertainties associated with input variables (Boardman et al., 2018). Moreover, they may fail to address the structural complexities of socio-environmental systems, leading to potential oversights in planning for uncertain outcomes (Helgeson & Li, 2022). In contrast, sophisticated models—including agent-based and system dynamics models—encompass these complexities and uncertainties in resilience planning and evaluation of candidate strategies. Such models, however, come with their own set of challenges, including intensive demands on time, financial resources, and data requirements (Mls et al., 2023; Bottero et al., 2020).

To overcome these challenges, there is a growing need for user-friendly, accessible models that provide comprehensive and reliable results for community resilience planning. The Co-DECIDR modeling approach addresses these needs by integrating Fuzzy Cognitive Mapping (FCM) with Benefit-Cost Analysis (BCA), harnessing the strengths of both methods and allowing for the consideration of both monetary and non-monetary valuation within resilience planning and providing an avenue by which community-level values can be assessed. This integrated approach systematically combines the qualitative depth of FCM with the quantitative precision of BCA, enabling planners to navigate through complex SES with greater clarity and effectiveness. Through more inclusive and transparent models like the Co-DECIDR approach, which incorporates economic factors and the broader socio-environmental context, we can enhance resilience interventions that equitably and effectively address the complexities and uncertainties of dynamic systems. Subsequent sections of this article will further demonstrate how the Co-DECIDR approach facilitates these outcomes.

2. Co-DECIDR

The Co-DECIDR approach employs two publicly available online tools: Mental Modeler (Gray et al., 2013a) for FCM and Economic Decision Guide Software (EDGe$) (Helgeson et al., 2017; Helgeson & O'Fallon, 2021) for BCA. Mental Modeler facilitates collaborative system modeling with stakeholders, capturing collective knowledge for disaster response prioritization and broader community concerns. EDGe$, developed by the National Institute of Standards and Technology (NIST), offers a standardized modeling tool for the economic evaluation of resilience investments. Together, these tools streamline the planning process, allowing for a nuanced analysis of strategies against the backdrop of economic limitations and the SES's inherent complexities.

Economic models are often employed to support resilience planning in SES by providing quantitative estimates of the costs and benefits associated with different interventions, scenarios, and policies (Gilbert & Ayyub, 2016). One widely used economic tool in this context is BCA, which helps with economic assessment of various resilience alternatives by quantifying the monetary values of net associated benefits and costs (Proag, 2021). However, as with participatory modeling techniques, relying solely on economic models for resilience planning can have several drawbacks. First, economic models may not capture the complex interactions and feedback between human and natural systems, potentially overlooking the non-market values and services. Such elements, including social cohesion, dignity, and well-being, cannot be readily converted into economic values. (Rogers et al., 2019; Rising et al., 2022). Second, economic models may reinforce structural racism as they prioritize economic efficiencies over social equity, contributing to the hindrance of achieving equity in resilience planning (Hendy et al., 2023). Third, these models may not adequately account for the uncertainty and unpredictability of SES dynamics, often assuming a stable or equilibrium state (Welsh, 2014; Berger & Marinacci, 2020; Helgeson & Li, 2022). Fourth, economic models often do not involve the active participation and collaboration of multiple stakeholders—such as local communities, governments, and researchers—each of whom may have different perspectives, values, and interests in the SES (Raciborski et al., 2022). Therefore, economic models for the resilience planning of SES should be complemented by other modeling approaches that can ensure a more robust and equitable response to the resilience challenges faced by communities.

Integrating economic models with the participatory modeling process is a promising approach to ensure the meaningful engagement of various disciplines and stakeholders, a vital aspect of comprehensive modeling for resilience planning in SES (Miles, 2018; Helgeson & Li, 2022). Such a holistic approach also assists in managing the inherent uncertainties that characterize SES. FCM is a participatory modeling technique that allows stakeholders and experts to collectively construct semi-qualitative cognitive maps that represent their mental models of the SES. These maps help to explain the complexities and interconnections within the system, facilitating better decision-making (Gray et al., 2015). However, FCMs are unitless and simulations show relative change under different scenarios without any temporal dynamics, which can be insufficient information for decision-makers. It can be vital to compare economic factors like direct costs or return on investment over different time horizons. By integrating FCMs with economic modeling tools (e.g., BCA) for resilience planning in SES, we can utilize both local expertise and systems modeling with economic evaluation of alternatives. The four steps in the Co-DECIDR process are summarized below and visualized in Figure 1.

Step 1: Develop a thorough definition of the scope of resilience the community will address in the modeling process. This entails identifying the key components of the SES under study, clarifying the community goals and values, and comprehending the interrelationships and dynamics among these system components. This foundational phase—critical for defining 'resiliency of what and for whom' (Meerow & Newell, 2021) —engages the stakeholders and invites them to use FCM to visually depict and assess the interactions among system components (Gray et al., 2013b). This process also highlights how system components can impact non-monetary community values. The participatory aspect of this step is crucial not only for understanding the system's complexity but also for fostering inclusiveness and knowledge sharing, which are instrumental in advancing GMP.

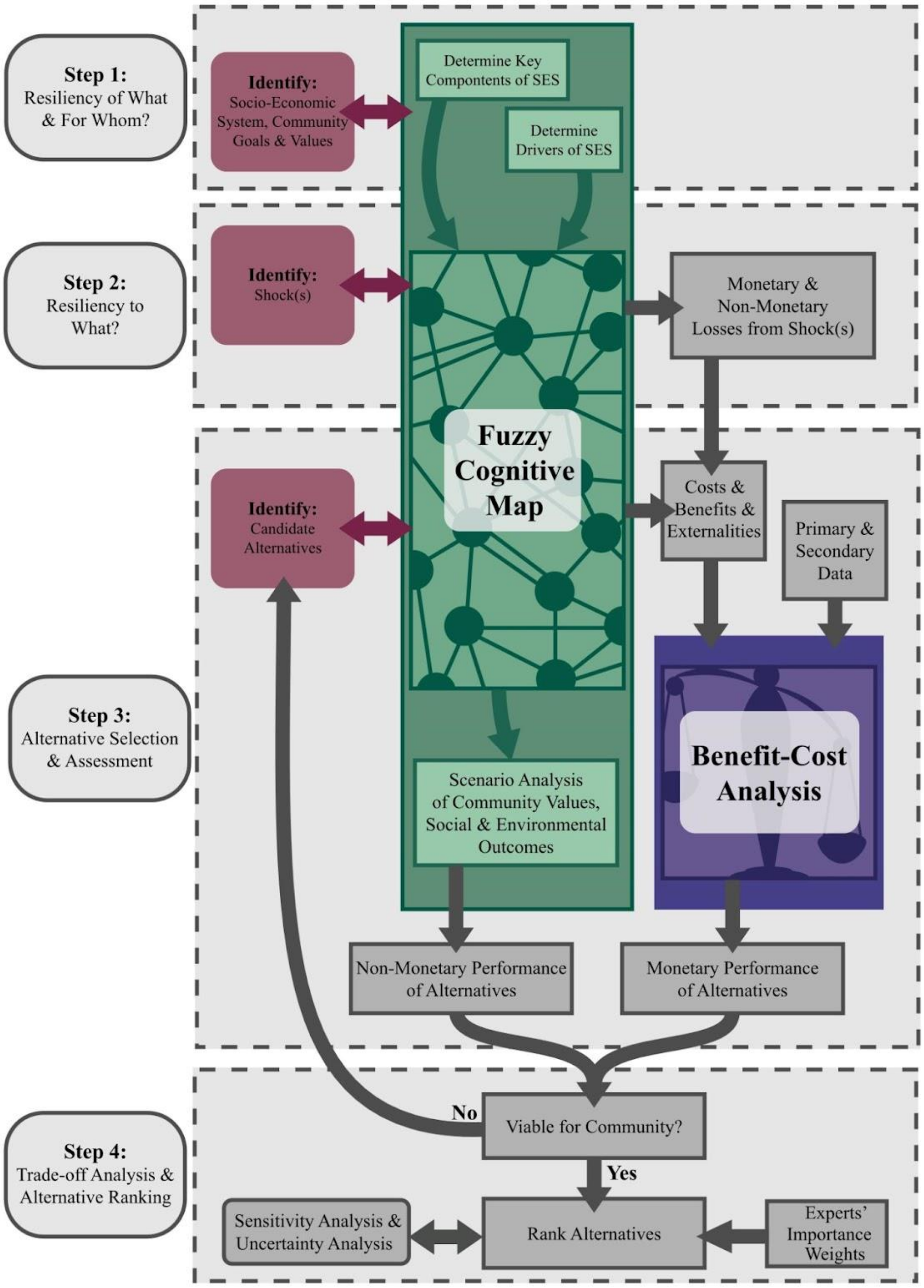

Figure 1: The four steps of the Co-DECIDR modeling approach.

Step 2: Determine potential shocks that could challenge the system's balance to assess the system's 'resilience to what' (Meerow & Newell, 2021). Anticipating various disruptions — whether they be environmental, economic, or social — and exploring both the potential monetary losses and non-monetary impacts is key to identifying shocks. Initiate a literature review to understand the impacts of similar shocks on comparable systems, laying a foundational knowledge base. Then, conduct a qualitative analysis of community narratives and mental models related to these shocks, utilizing FCMs to dive deep into localized perceptions. This labor-intensive endeavor is crucial for the nuanced impact assessment of shocks. The inclusion of local knowledge decreases structural uncertainty about the system's functions, enabling a more accurate assessment of both the direct and indirect effects of shocks on the system (Van Vliet et al., 2020). This is essential for enhancing resiliency planning, as it ensures that strategies are grounded in a comprehensive understanding of the community's specific needs and vulnerabilities.

Step 3: Select and evaluate candidate alternatives as coping strategies for the identified shocks. The narratives gathered from local experts through FCM serve as a valuable resource for choosing these candidate alternatives. Once the alternatives are determined, their effectiveness can initially be tested through FCM scenario analysis. This 'what-if' scenario analysis can be conducted in two distinct ways. The first approach involves creating a single FCM through group conversation with local experts, followed by running the scenario analysis (Jetter & Schweinfort, 2011). The second approach aggregates individual FCMs — each captured separately by local experts — to form a collective intelligence (CI) model, upon which scenario analysis is then conducted (Knox et al., 2023). These analyses examine how the selected alternatives impact the community-identified values and other system components, focusing on the non-monetary performance of the alternatives. These community-identified values represent what the community most values regarding its desirable future and can be captured through workshops and interviews (See section 4.1). To complement the qualitative impact assessment of each candidate alternative from the FCM scenario analysis, conducting a BCA is essential for the quantitative assessment of the economic feasibility of each alternative. This process requires identifying the associated benefits, costs, and externalities of each candidate alternative, which is crucial for gaining insights into their economic performance (Douthat et al., 2023). The outcomes from FCM scenario analysis can shed light on the externalities of each alternative at the community level, providing instrumental insights for BCA. Step 3 promotes GMP by incorporating local priorities and valuing descriptive knowledge for quantification and extending performance assessment beyond common metrics to include qualitative methods.

Step 4: Conduct a trade-off analysis to rank the alternatives based on their impacts on community-identified values and relevant economic outcomes. This step effectively merges the BCA outcomes of each alternative with the scenario analysis results from the FCM. Only those alternatives deemed viable by the community are ranked, ensuring the identification and prioritization of the most effective strategies for enhancing resilience. Given the iterative nature of the Co-DECIDR process, the initial results will be shared with community members and local experts to evaluate if the alternatives align with the community's criteria for viability. In this context, 'viability' refers to the acceptability and feasibility of the alternatives for the community. If any alternative is found non-viable according to the community's criteria, a new alternative should be selected, necessitating a revisit to steps 2 and 3 of Co-DECIDR. Conversely, if the alternatives are confirmed as viable by the community, a multi-criteria decision analysis (MCDA) is applied to the outcomes for a thorough ranking process. MCDA is used in resilience planning to evaluate and compare alternative candidates, enhancing decision-making for robust preparedness strategies (Abdullah et al., 2021; Gomes et al., 2023; Rezvani et al, 2023). Depending on the level of community engagement for final assessment of the alternatives, this step can significantly enhance the legitimacy of the resilience planning process, which is a crucial aspect of GMP. In addition, for this step, conducting sensitivity analysis and uncertainty analysis on BCA and MCDA results is highly recommended (Stewart, 2005; Maliene et al., 2018; Farrow et al., 2020). These analyses are crucial for evaluating the robustness and reliability of the rankings, ensuring a comprehensive assessment of each candidate alternative.

To test the application of Co-DECIDR, we developed two proof-of-concept examples. These examples were centered around the use of data collected by a community-engaged initiative, the Flint Leverage Points Project (FLPP)[1]. The primary goal of FLPP was to identify crucial leverage points capable of positively transforming Flint's food system (Hodbod & Wentworth, 2022; Schmitt-Olabisi et al., 2023). The objective of these proof-of-concept examples was to showcase how data obtained from such community-based projects could be efficiently integrated into the Co-DECIDR framework. This integration aims to facilitate the assessment of potential shocks and the evaluation of various candidate alternatives for coping with these shocks.

3. Proof-of-concept examples

Each proof-of-concept demonstration in this study includes one specific shock and two candidate alternatives that provide adaptations or coping strategies. During the FLPP data collection, participants from diverse communities and disciplines expressed concerns regarding numerous factors that could disrupt Flint's food

[1] https://www.canr.msu.edu/flintfood/

system. Among these factors, we selected two distinct yet representative shocks: a pandemic such as COVID-19 (representing a shock rooted in societal dynamics), and extreme weather events (originating from climate change).

3.1 COVID-19

The effects of COVID-19 on the food system and communities have been significant (Galanaksi, 2020; O'Hara & Toussaint, 2021), and clearly intensified in areas where food access is already difficult, such as Flint (Michigan USA). Some studies have investigated the impact of the pandemic on the food distribution sector—such as the temporary or permanent closure of food outlets during the pandemic (Yi et al., 2021; Bell & Taylor, 2023). These closures, in turn, had far-reaching consequences, resulting in the loss of revenue for their staff and food producers, while simultaneously reducing food access for the community (Yi et al. 2021). Furthermore, the pandemic caused consumers to face a substantial increase in food prices— especially for healthy, perishable food items (Lewis et al., 2023). As a result of these economic challenges, the number of food insecure individuals in Michigan surged by 18.7% during the pandemic (Michigan's Food Security Council, 2022), underscoring the critical impact on many communities' well-being. Beyond these socio-economic hardships, the impact of COVID-19 on public health and human lives cannot be overstated, as many individuals found themselves hospitalized or faced the tragic loss of family members, resulting in unimaginable damage to communities.

For this study, two distinct alternatives were selected as coping strategies to mitigate and adapt to the impacts of COVID-19 on the food system: 1) establishment of a new open-air (outdoor) farmers market and 2) opening a new food hub with delivery services that acts as a food processing plant. Various studies have affirmed the pivotal role of localized food systems in ensuring food security during crises (Worstell, 2020; Thilmany et al., 2021). To strengthen local and regional food systems, different business models can be employed. Notably, farmers markets emerged as a cornerstone of resilience during the pandemic, connecting local producers directly to consumers at a time when larger supermarkets grappled with empty shelves due to their reliance on national and international food supply chains (Wentworth et al., 2023). Additionally, the surge in consumer demand for food delivery during COVID-19 led to the consideration of local food processing hubs that offer online markets as a viable alternative (Gu et al., 2021). With individuals spending more time at home and greater inclination towards home-cooked meals, local food processing hubs offering delivery options for community members emerged as a promising solution. These strategies represent alternatives aimed at enhancing food system resilience in the face of pandemics.

3.2 Extreme weather events

Additionally, we selected extreme weather due to its impact on food systems and the relevance to resilience planning. Extreme weather events exacerbated by climate change, such as wildfires, tornados, heatwaves, or storms currently pose significant challenges for cities and urban planning. The main forms of extreme weather in Michigan are heatwaves and severe precipitation (EPA, 2016; MDHHS, 2018). These extreme weather events impact food systems in a few ways. First, transportation and distribution systems can be disrupted. Participants in FCM interviews described how deeply connected transportation is to community members' abilities to source the type, quality, and amount of food they want. Second, electricity outages and higher temperatures increase food spoilage and waste. Low-income, elderly, and disabled populations are particularly vulnerable to interrupted accessibility of food and various extreme weather-related health risks (White et al., 2010).

In this paper, we selected two alternatives that would lessen the impacts of extreme weather on the transportation system and food accessibility. These two alternatives are 1) installing bus shelters and 2) upgrading the limited number of convenience stores to healthy food outlets. There are approximately 1,200 bus stops for the fourteen lines that the Flint Mass Transit Authority (MTA) operates (MTA, 2023). While some currently have shelters, a vast majority do not. Bus shelters have multiple benefits, including benches to rest on and roofing and walls to protect riders from rain, sun, and wind. Stover and McCormack (2012) found shelters to be an effective intervention that ameliorated ridership losses from rain, particularly at high-use stops to increase usage by riders. Additionally, this alternative can enhance food accessibility for public transportation users during heatwaves and severe precipitation, making it easier for them to reach food sources without discomfort. For the BCA, we will model the construction and maintenance of 100 new bus shelters. The next alternative proposes transforming 10 existing convenience stores in different neighborhoods with limited access to fresh markets into 'healthy convenience stores'. This initiative is designed to enhance infrastructure and facilities within these stores to offer a wider range of fresh local products, including fruits, vegetables, meat, and dairy, ensuring higher diversity of choice and affordability. By collaborating with local producers, these health convenience stores will provide consumers — especially those without personal vehicles — easier access to healthy food options in their neighborhood, promoting better dietary habits and reducing food deserts. Moreover, shortening distances to food stores can enhance accessibility during extreme weather events.

4. Methods

4.1 Data collection

The data collection for our study primarily relied on the extensive efforts of the Flint Leverage Points Project (FLPP). Over a span of five years, a Michigan State University research team collaborated with a community partner, the Community Foundation of Greater Flint, and was advised by a broader Community Consultative Panel (CCP) composed of Flint community members active in different aspects of the food system. Forging a strong partnership allowed us to gain profound insights into various aspects of the Flint food system work (for a more detailed description of the FLPP research phases, see Table 1 in Schmitt-Olabisi et al. 2023), which built on many years of local, community-engaged research (Alaimo et al., 2008; Ober Allen et al., 2008; Masson-Minnock and Stockmann, 2010; Sadler et al., 2015). An array of data collection methods — including literature reviews, workshops, surveys, and interviews — served as valuable tools to comprehensively capture the essence of the Flint food system (Schmitt-Olabisi et al., 2023).

Through the initial phases of the FLPP, visioning workshops were conducted during which Flint community members described their desired food system. Based on these conversations and an inductive analysis of interview transcripts, various food system values were identified (Belisle-Toler et al., 2021). Subsequently, two additional workshops were held with local and state government leaders, as well as philanthropic organizations working on the Flint food system, to identify the values they prioritized for the food system (Wentworth et al., 2022). As a result of these dialogues, a total of seven synthesized community-identified values (CIVs) emerged as pivotal to the Flint food system[2]: *affordability, availability, nutritious foods, community empowerment, education, partnership,* and *quality of life is respected* (Figure 2). For this study, these previously determined CIVs were utilized to evaluate the potential impacts of different shocks and alternatives on the Flint food system (Co-DECIDR Steps 2 and 3) and served as non-monetary criteria in the trade-off analysis (Co-DECIDR Step 4).

The second data set used in this study comprised individual FCMs previously collected during the mental modeling phase of the Flint Leverage Point project (Schmitt-Olabisi et al., 2023). As part of this phase, 51 interviews with food system experts were conducted to capture their mental models of the Flint food system dynamics and the interactions among various system components (Knox et al., 2023). These individual FCMs were developed through semi-structured interviews, and followed by an inductive qualitative analysis to categorize system components as detailed in Knox et al., 2023 . These previously collected data and foundational findings were critical for Step 1 of Co-DECIDR, which involves understanding the Flint food system dynamics based on individual narratives and fuzzy cognitive maps. Additionally, for this study, the individual FCMs and interview transcripts were utilized to analyze the non-monetary losses associated with the selected shocks and to guide the identification of potential co-costs and co-benefits of the proposed alternatives (Co-DECIDR Steps 2 and 3) Furthermore, the collective intelligence model of the Flint food system, previously created by Knox et al. (2023), was used for scenario analysis and the evaluation of shocks and alternatives to assess how each alternative impacts the non-monetary criteria (the 7 CIVs) in the Flint food system (Co-DECIDR Step 3).

Data previously collected through the FLPP were complemented by newly gathered primary and secondary data sources for the BCA. This approach was adopted to enrich our understanding of the potential impacts that various selected shocks could have on the Flint food system, as well as to determine the required input data for EDGe$ associated with each candidate alternative for the BCA. These additional data sources encompassed a wide spectrum of information, including but not limited to statistical records, historical trends, government reports, and academic studies (detailed in Supplementary Material B).

[2] https://www.canr.msu.edu/flintfood/resources-and-publications/values-for-the-flint-food-system

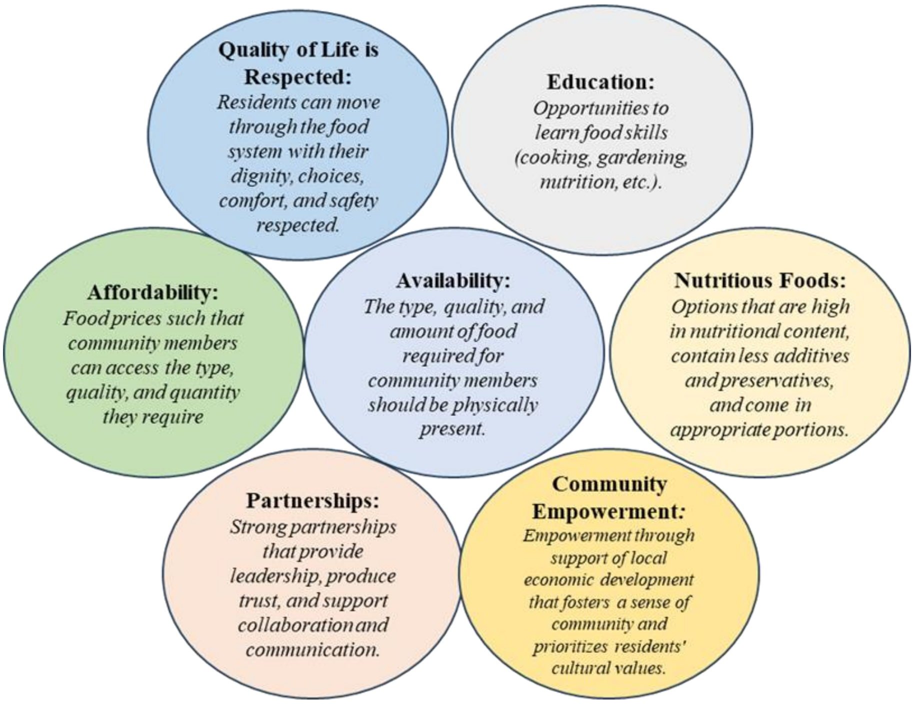

Figure 2: Seven synthesized community-identified values (CIVs) and associated definitions, that are representative of desired Flint Food System.

Additionally, the data collection included four semi-structured interviews with experts who have extensive experience in Flint's food system. These experts have worked on the organizational/non-profit side of the food system and employed their academic training to work in settings where they can make policy changes (i.e. by serving on groups like the food policy council). The interviews served two main purposes: first, to confirm whether the suggested alternatives were practical and could be implemented within the Flint food system; and second, to determine the importance of each criterion, both monetary and non-monetary, that would be used in the trade-off analysis. By integrating this multifaceted dataset with the CIVs and the insights garnered from the FCM interviews, we aimed to construct a robust analytical foundation for Co-DECIDR, one that could holistically assess the vulnerabilities and opportunities within Flint's food system.

4.2 Data analysis

4.2.1 FCM analysis

For the FCM analysis, findings from the previously published paper (Knox et al., 2023) were utilized to understand the dynamics of the Flint food system. These individual FCMs were collected through semi-structured interviews, and were followed by an inductive qualitative analysis (Bingham & Witkowsky, 2021) to categorize system components (detailed in Knox et al., 2023). This foundational analysis played a critical role in Step 1 of Co-DECIDR (resilience scope) to reveal how the components of Flint's food system impact seven CIVs and to understand the dynamics of the Flint food system based on individual narratives and Fuzzy Cognitive Maps. This qualitative analysis lays the foundation for our subsequent assessments.

The interview instrument for collecting FCMs included five sections, with Section 4 specifically dedicated to exploring the impact of COVID-19 (Knox et al., 2023). For this study, transcript segments related to COVID-19 were qualitatively assessed to identify potential losses and mitigation strategies for the pandemic's impacts, enriching the analysis for Steps 2 and 3 of the Co-DECIDR process. Conversely, no specific questions addressed extreme weather events during the FCM interviews. Consequently, a review of the interview transcripts was conducted to extract any narratives on how such events might affect the Flint Food System, although only a few respondents discussed this topic. To evaluate the impacts of shocks and alternatives on Flint's food system, a previously developed collective intelligence model by Knox et al. (2023) was utilized. This model was created by aggregating individual FCMs using Principal Component Analysis (PCA) to group participants with conceptually similar maps, (as detailed in Knox et al., 2023). For this study, the existing CI model was modified (as described in Supplementary Material A) and applied in scenario analysis to investigate how selected shocks and candidate alternatives as coping strategies affect Flint's food system, specifically the seven CIVs (Step 2 & 3 of Co-DECIDR). This scenario analysis helped to understand the non-monetary effects of alternatives on Flint's food system, especially those for which it may not be appropriate to attempt to monetize through revealed or stated economic techniques.

4.2.2 Benefit cost analysis

To assess the economic feasibility of the candidate alternatives within each proof-of-concept example, we employed the NIST Economic Decision Guide Software (EDGe$) Online Tool (Helgeson et al., 2017; Helgeson & O'Fallon, 2021). EDGe$ is capable of providing either point estimates or probability distributions for key financial indicators, including the benefit-cost ratio (BCR) and annual return on investment (AROI). To initiate the BCA with EDGe$, it is essential to determine the planning horizon, discount rate, and probability of occurrence for each shock. For the primary BCA assessment, we set a planning horizon of 30 years and a discount rate of 5%. The estimated probability of a pandemic akin to COVID-19 occurring is approximately once every 129 years, with a 95% confidence interval ranging from 120 to 140 years (Marani, 2021). For calculating the probability of heatwaves and severe precipitation events, we utilized 50 years of weather data for Flint. Our analysis revealed an average occurrence of three heatwaves and six severe precipitation events per year, as reported by NOAA (2023).

In the subsequent phase of the BCA with EDGe$, we conducted a comprehensive assessment of costs, benefits, and externalities for each candidate alternative. Costs encompassed direct expenditures, including initial implementation and ongoing maintenance expenses. Conversely, benefits represented the positive outcomes and more tangible financial gains associated with each alternative. Additionally, we accounted for externalities—whether positive or negative—arising from the potential impacts of each alternative on third parties and the environment, relying on the outputs provided by FCMs and primary/secondary data collection. A comprehensive list of EDGe$ input values and data sources for all alternatives is available in Supplementary Material B. To account for the associated uncertainty in input data, we adopted three distinct scenarios for conducting the BCA: a 'best case' with the lowest costs and highest benefits/externalities, a 'mean case' with average values, and a 'worst case' with the highest costs and lowest benefits/externalities. Table 1 illustrates an example input for the 'open-air farmers market' alternative within the COVID-19 scenario. This analysis — integral to Co-DECIDR's third step — provided crucial insights into the monetized expected value of each alternative.

4.2.3 Trade-off analysis

After an initial assessment of the monetary and non-monetary performance of candidate alternatives, trade-off analysis (i.e., Co-DECIDR step 4) serves as a vital tool to guide the identification of appropriate solutions, taking into account both societal priorities and financial considerations. As outlined in Section 2, before moving forward with the ranking process, the community must assess the viability of the proposed alternatives. For our proof-of-concept examples, we utilized semi-structured interviews with four Flint food system experts to first thoroughly present the detailed operational aspects of each proposed alternative. Following this explanation, we asked these experts to assess the acceptability and feasibility of each option. This process ensured that the alternatives were viable, making them eligible for the subsequent ranking process.

To ensure a nuanced evaluation, the Co-DECIDR framework incorporates the Multi-Criteria Decision Analysis (MCDA) techniques within its trade-off analysis (see Kiker et al., 2005; Dodgson et al., 2009 for a variety of MCDA techniques). This approach systematically combines the outputs from the FCM scenario analysis, based on the CI model, with the BCA results from the EDGe$ to provide a clear and systematic ranking of alternatives. Figure 3 illustrates this process. Initially, all monetary and non-monetary results were transformed into normalized scores ranging from 1 to 100. The normalization process guarantees that scores for each criterion are proportionately adjusted within this range, thus allowing for a fair comparison of performance across varied metrics. Furthermore, through semi-structured interviews with experts in Flint's food system, the evaluation process was refined by the determination of importance weights for each criterion, ensuring that the final scores accurately represent the prioritized values of the community.

Table 1: The required EDGe$ input data for benefit-cost analysis of open-air farmers market alternative. The input data for all the alternatives is available in Supplementary Material B.

Item	Classification	Value		
		Best Case	Mean Case	Worst Case
Rent for the site	Cost	$3,000	$15,000	$24,000
Initial Supplies and Miscellaneous	Cost	$3,500	$6,000	$9,000
Market Management and Staffing	Cost	$80,000	$100,000	$125,000
Licenses and Permits	Cost	$95	$150	$255
Insurance	Cost	$1,000	$2,000	$3,000
Utility and Services	Cost	$1,750	$4,200	$7,000
Marketing and Promotions	Cost	$4,500	$5,400	$6,000
Revenue from Vendor Fees	Benefit	$78,750	$55,500	$26,250
Health Benefits	Externality	$50,000	$35,000	$20,000
Spillover Effect on Nearby Businesses	Externality	$66,570	$57,500	$44,380
Reduction in Losses of Closed Food Outlets	Externality	$252,000	$210,000	$170,000
Reduction in Food Insecure People	Externality	$62,500	$50,000	$37,500
Fatalities Averted	Human Life	10	8	6

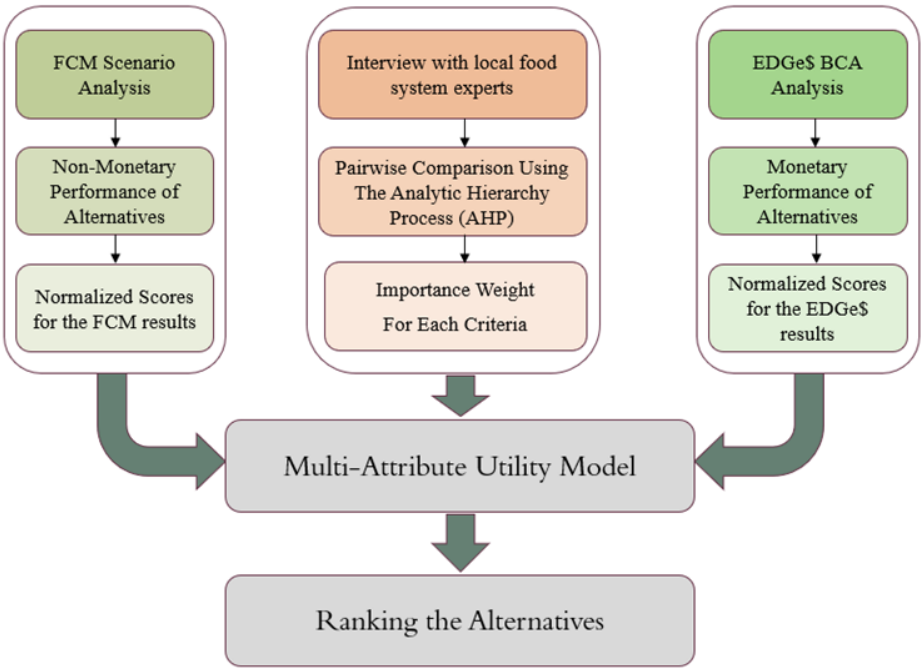

Figure 3: The information flow of FCM scenario analysis outputs, EDGe$ results, and importance weights for monetary and non-monetary criteria for trade-off analysis and ranking process.

The Analytic Hierarchy Process (AHP), a well-structured method for organizing and analyzing complex decisions, was used to determine these importance weights (Saaty, 2003; Dodgson et al., 2009). Through interviews with four local food system experts, the AHP's pairwise comparison method was employed to establish the relative significance of each criterion. The publicly available AHP-OS online tool was used to facilitate the calculation of these weights in a user-friendly and efficient way (Goepel, 2018). After individual responses were collected, the geometric mean method was applied to aggregate the importance weights from all respondents (Xu, 2000). With the importance weights and normalized scores for both monetary and non-monetary criteria in hand, a multi-attribute utility model (MAUM) is utilized to compute the final scores for each of the candidate alternatives. (See Benromdhane, 2021 for the detailed description of MAUM formulas.)

4.2.4 Sensitivity and uncertainty analysis

The principles of GMP underscore the significance of sensitivity and uncertainty analysis in resilience planning (Perz et al., 2013). Adhering to these principles ensures that models employed to support decision-making processes are not only robust, but also reliable. In complex SES characterized by escalating environmental challenges and economic uncertainties, these analyses become imperative as they enable us to systematically evaluate how variations in key parameters can exert influence on the outcomes of resilience planning models.

We conducted a sensitivity analysis to explore the impact of two critical parameters in BCA: the discount rate and the planning horizon. The discount rate is a fundamental factor in evaluating the present value of future costs and benefits, potentially affecting the economic feasibility of candidate alternatives (Boardman et al., 2018). To assess its influence, we tested the sensitivity of our model's outcomes by varying the discount rates at 3%, 5%, and 7%. Furthermore, the planning horizon is another pivotal aspect of resiliency planning, determining the timeframe over which benefits, costs, and externalities are considered and directly impacting the long-term effectiveness of proposed strategies. In our analysis, we investigated planning horizons spanning 20, 30, 40, and 50 years. This allowed us to gauge how different discount rates and planning horizons could alter the cost-benefit analysis results, final scores, and ranking of alternatives in this study.

In conjunction with sensitivity analysis, the influence of the uncertainty inherent in BCA input data on the final scores and the prioritization of alternatives across the spectrum of worst-case, mean-case, and best-case scenarios was meticulously evaluated. The details of the inputs utilized for each scenario and their data sources can be found in Supplementary Material B. This approach provided a more comprehensive understanding of the uncertainties associated with resiliency planning, helping to make more informed decisions in the face of an uncertain future.

5. Results

5.1 Monetary and non-monetary losses

The COVID-19 pandemic and extreme weather events have significantly disrupted food systems worldwide, with considerable impact on food production, distribution, and consumption. Flint's food system, like others, faced substantial challenges during these times. This section outlines the monetary losses and non-monetary impacts extracted from FCM narratives, focusing on key areas of disruption.

5.1.1 Monetary losses regarding COVID-19

The pandemic led to disruptions in both global and national food supply chains, causing a notable increase in food prices. From December 2019 to December 2020, food prices in the United States increased by approximately 3.4%, and from December 2020 to December 2021, by about 7% (Bureau of Labor Statistics, 2022). This inflation significantly burdened food consumers, impacting their economic accessibility to food products (Lewis et al., 2023). The increased food prices contributed to more than $34 million in losses for the Flint community during the first two years of COVID-19. The estimated value is based on the 33854 households in Flint and average food spending of $839 per month per family of two in Michigan (USCB, 2022; Uphomes, 2023).

Moreover, health and safety guidelines during the pandemic necessitated the closure of many food outlets and restaurants, leading to the unemployment of many workers within the food system. In Flint, specifically, the unemployment rate surged by 19.5% (Jablonski et al., 2021). This increase in unemployment was notably influenced by the closure of approximately 16.5% of food outlets, which included 32 restaurants and 10 convenience stores in Flint (Bell & Taylor, 2023). These closures resulted in approximately $4.5 million in economic losses. Unemployment and other circumstances related to the pandemic increased the number of food-insecure individuals. Between 2018 and 2020, Flint experienced a notable increase in food insecurity, with rates climbing from 15% to 21% (Jablonski et al., 2021). By assuming a 4% increase due to the impact of COVID-19, and based on Flint's population of 79,000 (USCB, 2022), this adjustment translates to approximately 4,000 more residents facing food insecurity. Based on the estimated cost of healthcare associated with food insecurity, $250 per capita (Michigan’s Food Security Council, 2022), this led to about $1 million in losses.

5.1.2 Non-monetary losses regarding COVID-19

Based on the narratives collected from the FCM interviews, the non-monetary losses of COVID-19 on the Flint community are multifaceted and profound, affecting various aspects of daily life and community well-being. The pandemic has significantly increased isolation and reduced community connections, which led to mental health deterioration and underscored the critical need for empathy and care in managing community relationships. Additionally, it disrupted nutritional and educational programs, particularly affecting students' access to nutrition and educational resources due to the shift to virtual learning environments. The demand for emergency and supplemental food services surged as the community sought to navigate the challenges of accessing food. Moreover, several people decreased their purchases from indoor big supermarkets because of safety concerns, highlighting the importance of food delivery services for those unable or unwilling to venture out. Furthermore, health disparities among different regions in Flint became more evident. Together, these factors illustrate the complex web of non-monetary losses that extend beyond financial metrics, deeply affecting the Flint community during the pandemic. Two example quotes from participants in FCM interviews underscore these points:

Participant ID-117*: “When you think about some who have lost their jobs due to COVID-19, not having access to get food, the mental piece is impactful. And we still are not sure how deep this is going. We're still learning as we go on this part. But I do truly feel that the mental state has suffered so much*.”

Participant ID-147*: “And that was real- it's been horribly impacted by COVID. Yeah, youth food access is really negatively affected. It changed where kids could get that. And it just changed it so, so much. And so many of those systems that we took for granted, were now changed. And the problem was that it continuously changed.”*

5.1.3 Monetary losses regarding extreme weather events

Based on 50 years of NOAA Weather Service data (2023), Flint experiences an average of three heatwaves and six severe precipitation events annually. Yue & Kahn (2019) found that severe precipitation increases vehicle accidents by 40%. With Genesee County's average daily crashes at 29 (CJIC, 2021) and Flint accounting for 20% of the county's population, this results in an additional 8.12 crashes in Flint during severe precipitation. Using USDOT (2023)'s valuations — $12,172,415 per fatal crash and $300,328 per injury crash — these precipitation events are estimated to cause economic impacts of approximately $764,033 and $529,190 per storm in Flint, respectively. During heatwaves, the incidence of heat-related illnesses (HRI), such as heat stroke and heat exhaustion, increases and can be life-threatening. These conditions particularly impact outdoor workers and those lacking access to shade, rest, and water (Anderson & Bell, 2011; Schmeltz et al., 2016). On average, Genesee County experiences 15 HRI cases per heatwave (MDHHS, 2018). For Flint, which represents 20% of the county's population, this translates to about 5 cases. Given the cost of $8,965 per HRI case (Schmeltz et al., 2016), the financial burden on Flint amounts to $44,825 per heatwave. These weather-related challenges not only pressure public health and safety systems but also disrupt the local food system, affecting both supply chains and food accessibility in Flint.

Electricity outages from storm damage leads to significant costs, including lost productivity, health issues, and food spoilage. The DOE (2013) estimates that annual weather-related outages cost between $81 and $157 per capita. In Flint, assuming 25% of its population is affected, this translates to annual losses between $1,632,717 and $3,164,649. Outages also increase food waste; a 5% rise in waste due to outages amounts to 80,628 lbs of additional food waste for Flint. Furthermore, food storage life decreases by half with every 2-3°C increase in temperature (Vermeulen et al., 2012). Assuming a 5% increase in food waste during heatwaves, it leads to 8,466 lbs for Flint. Considering the cost of $1.53 per pound of wasted food (Buzby & Hyman, 2012), this results in $61,680 in losses per severe precipitation event and $12,953 per heatwave.

5.1.4 Non-monetary losses regarding extreme weather events

While FCM interview participants did not directly address the impact of extreme weather events on the Flint food system, their narratives shed light on residents' challenges with food accessibility. These challenges include the scarcity of adequate grocery stores in certain areas, difficulties accessing frequently visited food outlets via public transport, and an increased reliance on emergency food systems, such as food banks, due to limited food access. The importance of these insights becomes even more evident when considering the broader context of transportation's role in accessing food. Among the 51 participants, 34 highlighted "Access to Transportation" in their FCMs, underscoring transportation as a critical factor for community members to obtain the food they desire in terms of type, quality, and quantity. This emphasis on food accessibility illustrates its foundational role in addressing food security challenges in Flint. Severe precipitations and heatwaves further complicate these issues for the Flint community, highlighting the interconnectedness of weather, transportation, and food security in shaping residents' daily lives and well-being. The quote below from one of the FCM interviewees demonstrates an example challenge related to the food accessibility.

Participant ID-103*: "There are [a] lot of barriers to transportation and gaps to being able to get to a location. Especially when you're talking about taking home groceries if you're on the bus and it's very cumbersome, especially if you're managing small children. And safety, I think of ice and snow, right? Trying to get on and off a bus with two or three bags of groceries and a toddler and an infant? It's near impossible.*"

5.2 Evaluation of alternative candidates for coping with COVID-19

By running scenarios through the CI FCM model, we investigated the non-monetary impacts of two alternative strategies for coping with COVID-19 on CIVs, as demonstrated by Figure 4. Both alternatives demonstrated a considerable positive impact on the CIVs of *availability*, *nutritious food*, and *quality of life is respected*; both strategies are capable of providing fresh, local products to consumers in a safer and more comfortable manner. When it comes to CIVs of *education*, *community empowerment*, and *partnership*, however, open-air farmers markets have a more favorable impact as they enhance the direct sale of products from local producers to consumers, can offer educational training for their customers, and shorten the supply chain, which can be more resilient during pandemics. *Affordability* was the only CIV where both alternative strategies had a negative impact, possibly because they do not benefit from economies of scale and may offer slightly higher prices to their customers. Overall, the open-air farmers market appears to be a more effective alternative than local food delivery in addressing the CIVs.

When comparing the economic feasibility of alternatives with a consideration of a 5% discount rate and a 30-year planning horizon, the food hub with delivery services demonstrates better economic performance in mean and best-case scenarios. The open-air farmers market, however, has a slight advantage in the worst-case scenario. Table 2 presents some outputs — BCR and AROI — from the EDGe$ online tool for these scenarios, both including and excluding externalities. Incorporating externalities accounts for the economic impacts on the community and third parties. This approach ensures that all social and environmental benefits and costs are integrated into our economic evaluation. Therefore, only outputs with externality have been considered for the evaluation of alternatives. (See Supplementary Material B for the detailed costs, benefits, and externalities associated with each alternative).

Regarding different scenarios, the BCR improves for the open-air farmers market, moving from 0.79 in the worst case to 2.9 in the best possible situation. The same pattern is recognized in the AROI, which goes from a low end of -0.71% in the worst-case to a much better 6.34% in the best-case scenario. On the other side, the food hub with delivery services begins with a lesser BCR of 0.73 in the worst-case scenario but ultimately surpasses the open-air farmers market in the best-case scenario with a BCR of 4.37. The AROI for the food hub, starting at -0.9% in the worst-case scenario, significantly increases to 11.25% in the best-case scenario, exceeding that of the open-air farmers market. The broader variance in BCA and AROI across scenarios for the Food Hub indicates a higher degree of uncertainty associated with this alternative compared to the open-air farmers market. The sensitivity of these results against different discount rates and planning horizons is further investigated in Section 5.5.

Table 2: BCA results from EDGe$, demonstrating benefit-cost ratio (BCR) and annual return on investment (AROI) of candidate alternatives for COVID-19.

Alternatives	Economic Feasibility Metrics	Without Externalities			With Externalities		
		Worst Case	Mean Case	Best Case	Worst Case	Mean Case	Best Case
Open-Air Farmers Market	BCR	0.4	0.83	1.62	0.79	1.55	2.9
	AROI (%)	-2	-0.58	2.06	-0.71	1.84	6.34
Food Hub with Delivery Services	BCR	0.36	1.05	2.13	0.73	1.95	4.37
	AROI (%)	-2.12	0.18	3.77	-0.9	3.17	11.25

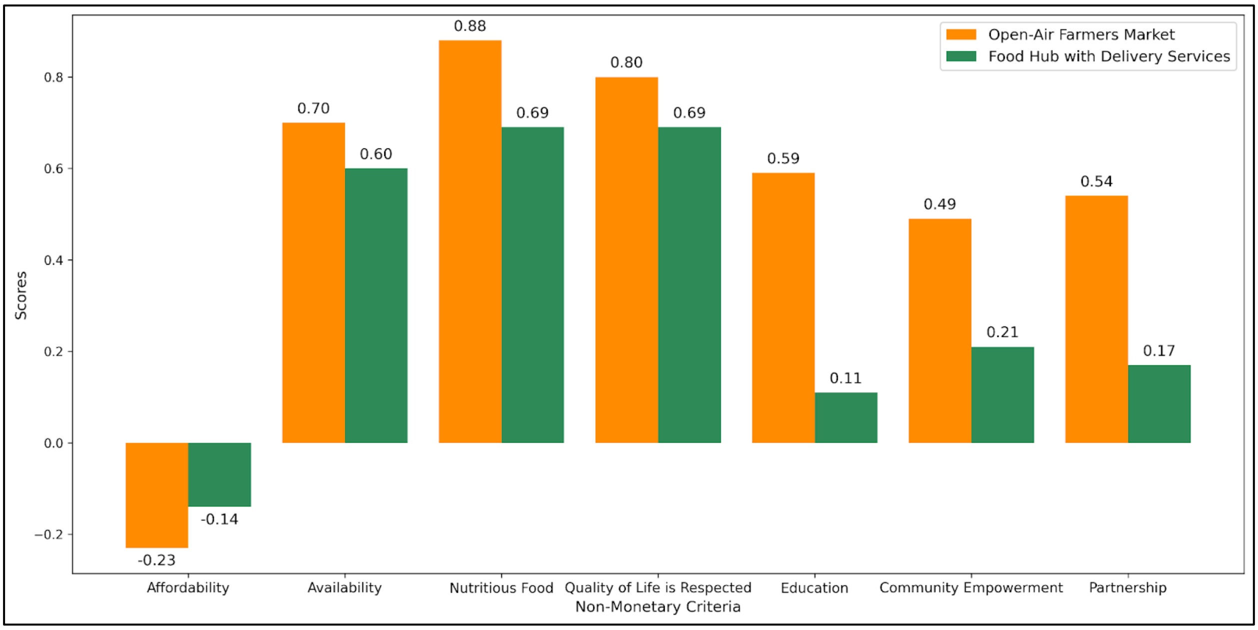

Figure 4: Scores of FCM scenario analysis for the candidate alternatives against COVID-19. Scores could vary from -1 to +1.

5.3 Evaluation of alternative candidates for extreme weather events

The non-monetary effects of the bus shelters were significant on some of the CIVs as illustrated in Figure 5. The bus shelter initiative substantially boosts three CIVs, *availability*, *nutritious food*, and *quality of life is respected*, underscoring the role of enhanced transportation facilities in increasing food source accessibility and overall community well-being. This alternative, however, does not considerably advance *education*, *partnership*, or *community empowerment*. Conversely, healthy convenience store improvements moderately enhance *availability*, *quality of life is respected*, and *nutritious food*, showing that localized store enhancements can offer immediate, but limited benefits in food access. Both alternatives exert minimal effects on *education*, *community empowerment*, and *partnership*, suggesting the need for complementary programs to strengthen these particular CIVs. In contrast to the COVID-19 strategies, which negatively affected *affordability*, these alternatives positively impact *affordability*, allowing community members to utilize public transport and access proper food outlets or find necessities within their neighborhoods.

Table 3, derived from EDGe$, indicates that both alternatives provide better results in the presence of externalities, with bus shelters showing a BCR increase from 0.047 to 0.244 and an AROI improvement, although remaining negative, from -3.17 to -2.51 from the worst to the best case. Healthy convenience stores exhibit a stronger economic performance, with the BCR jumping from 0.89 to an impressive 3.48 and the AROI turning positive, ranging from -0.37 to 8.27, indicating a considerable return in the best-case scenario.

Healthy convenience stores hold a substantial economic advantage in both mean and best-case scenarios, suggesting that this alternative can be a proper choice in scenarios that consider the full array of externalities (i.e. strengthening local economy, enhancing health and nutrition, and saving energy). Considerable variance existed in economic performance across different scenarios, especially for healthy convenience stores, which indicates a higher level of uncertainty. The more conservative economic performance of bus shelters may appeal to decision-makers prioritizing stability. The sensitivity of these results to variations in discount rates and planning horizons is a critical factor and is further examined in Section 5.5.

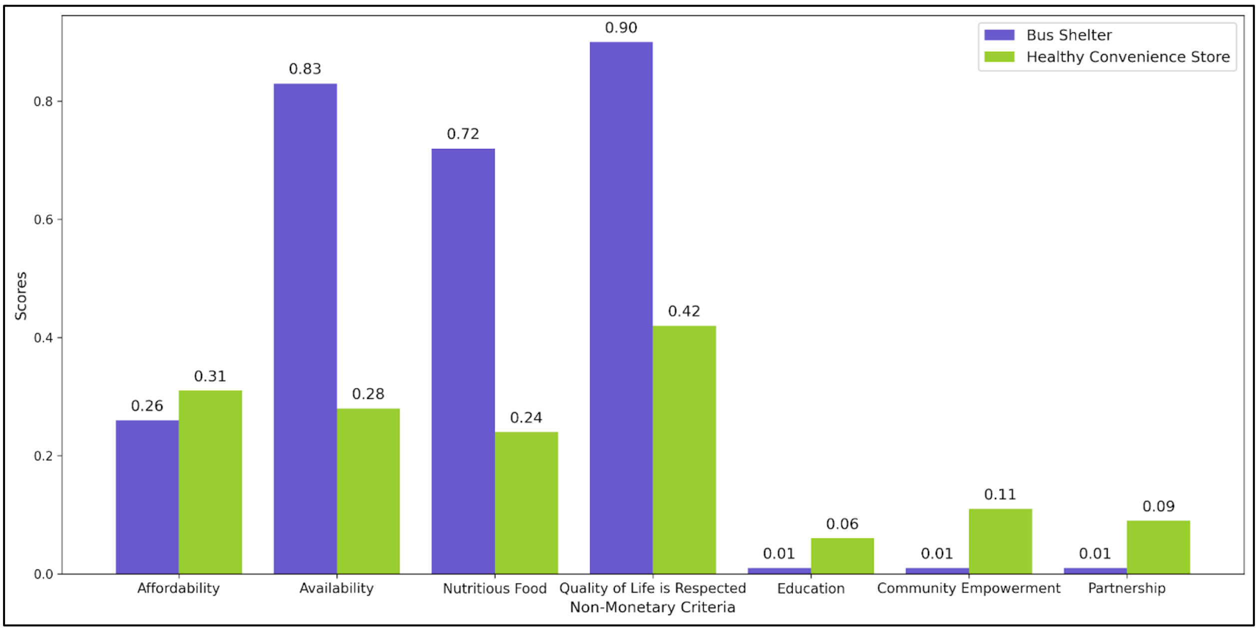

Figure 5: Scores of FCM scenario analysis for the candidate alternatives against extreme weather events. Scores could vary from -1 to +1.

Table 3: BCA results from EDGe$, demonstrating benefit-cost ratio (BCR) and annual return on investment (AROI) of candidate alternatives for extreme weather events.

Alternatives	Economic Feasibility Metrics	Without Externalities			With Externalities		
		Worst Case	Mean Case	Best Case	Worst Case	Mean Case	Best Case
Bus Shelters	BCR	0.007	0.034	0.096	0.047	0.113	0.244
	AROI (%)	-3.3	-3.21	-3.01	-3.17	-2.95	-2.51
Healthy Convenience Store	BCR	0.41	0.79	1.48	0.89	1.81	3.48
	AROI (%)	-1.97	-0.7	1.6	-0.37	2.71	8.27

5.4 Ranking of criteria and alternatives

After capturing the perceptions of different experts on the importance weights for various dimensions — both monetary and non-monetary — and associated criteria, a geometric mean was calculated to aggregate these insights. Collectively, experts assigned greater significance to non-monetary aspects, which was reflected in the importance weight that was notably higher for these aspects compared to their monetary importance weight (Table 4). Upon normalization of weights across the nine criteria, *quality of life is respected* emerged with a significant weight of 0.2204, followed by *community empowerment* at 0.1172, signifying these as the top priorities among the seven CIVs. Conversely, *nutritious food* and *education* were considered less critical, with weights of 0.0490 and 0.0324, respectively, occupying the lower end of the spectrum. In the monetary dimension, the BCR was predominant with the highest importance weight of 0.2509.

Table 4: Weights summary of dimensions and criteria. The "Local Weights" represent the relative importance of criteria within their respective dimensions (e.g., non-monetary or monetary), while "Global Weights" represent the overall importance of each criterion across all dimensions combined. Local and global ranks indicate the priority order of each criterion within its dimension and across all dimensions, respectively.

Dimension	Local Weights	Criteria	Local Weights	Local Rank	Global Weights	Global Rank
Non-Monetary	0.6733	Availability	0.1323	5	0.0891	5
		Affordability	0.1556	3	0.0711	7
		Education	0.0481	7	0.0324	9
		Partnership	0.1399	4	0.0942	4
		Quality of Life is Respected	0.3273	1	0.2204	2
		Community Empowerment	0.1740	2	0.1172	3
		Nutritious Food	0.0728	6	0.0490	8
Monetary	0.3267	Benefit to Cost Ratio	0.7679	1	0.2509	1
		Annual Return on Investment	0.2321	2	0.0758	6

In examining the normalized scores for CIVs and economic criteria across different candidate alternatives, nuanced trade-offs were observed. As Table 5 shows, among the COVID-19 alternatives, the open-air farmers market ranked first with a final score of 61.62, followed by the food hub with delivery services in second place. The open-air farmers market excelled in non-monetary aspects, scoring 79.17 compared to 70.31 for the food hub with delivery services. However, it underperformed in monetary terms, scoring 31.02 versus 38.57. This inverse relationship highlights a common trade-off where a strategy that excels in community-driven criteria may not be as strong monetarily. Moreover, for alternatives addressing extreme weather events, healthy convenience stores achieved the highest rank with a final score of 53.64, while the bus shelters ranked second with a final score of 49.50. The bus shelters performed well in non-monetary aspects with a score of 74.39 but faced a significant trade-off due to its low monetary score of 3.90. In contrast, healthy convenience stores maintained a more balanced profile, with closer non-monetary (62.97) and monetary (35.93) scores, resulting in its higher normalized final score of 53.64. These findings underscore the complexity of resilience planning, where both monetary and non-monetary factors must be weighed to discern the most effective approach. The higher final score for the open-air farmers market indicates that while monetary components are critical, incorporating non-monetary values is indispensable for holistic community-based resilience planning.

5.5 Sensitivity analysis and uncertainty analysis

5.5.1. Sensitivity to discount rate and planning horizon

The sensitivity analysis performed on the final scores, considering variations in discount rates (DR) and planning horizons (PH), underscores the robustness in the ranking of alternative strategies. Based on this analysis, the final scores for each alternative candidate remained within unique, non-overlapping ranges regarding the 12 different DR and PH combinations (see detailed explanation of these combinations in Section 4.2.4). This demonstrates consistent stability in the rankings under the mean-case scenario, ensuring that the relative performance of each strategy remains unaffected by variations in financial forecasting for our proof-of-concept examples. Detailed results for the worst-case, mean-case, and best-case scenarios are provided in Supplementary Material C, which reinforces the reliability of these rankings despite the alterations in DR and PH. While the variation in these BCA input parameters did not significantly affect the outcomes for our proof-of-concept examples, their consideration remains critical for comprehensively accounting for parameter uncertainty in resilience planning.

Table 5: Normalized Final Score Calculation. The Open-Air Farmers Market ranked first among COVID-19 alternatives. Healthy Convenience Stores ranked first for extreme weather alternatives.

		Normalized Evaluation Scores for COVID-19 Alternatives		**Normalized Evaluation Scores for Extreme Weather Alternatives**	
Criteria	Global Weights	Open-Air Farmers Market	Food Hub with Delivery Services	Bus Shelter	Healthy Convenience Stores
Availability	0.0891	85.0	80.0	91.5	64.0
Affordability	0.0711	38.5	43.0	63.0	65.5
Education	0.0324	79.5	55.5	50.5	53.0
Partnership	0.0942	77.0	58.5	50.5	54.5
Quality of Life is Respected	0.2204	90.0	84.5	95.0	71.0
Community Empowerment	0.1172	74.5	60.5	50.5	55.5
Nutritious Food	0.0490	94.0	84.5	86.0	62.0
Benefit to Cost Ratio	0.2509	31.0	39.0	2.3	36.2
Annual Return on Investment	0.0758	31.1	37.1	9.3	35.0
	Normalized Non-Monetary Score	**79.17**	**70.31**	**74.39**	**62.97**
	Normalized Monetary Score	**31.02**	**38.57**	**3.90**	**35.93**
	Normalized Final Scores	**61.62**	**58.36**	**49.50**	**53.64**
	Ranking for Alternatives	**(Rank 1st)**	**(Rank 2nd)**	**(Rank 2nd)**	**(Rank 1st)**

5.5.2 Sensitivity to importance weights

The sensitivity analysis, as illustrated in Figure 6, sheds light on the diverse perspectives among four experts when assigning importance weights to monetary and non-monetary criteria, and how these variances impact the final scores and rankings of the alternative strategies. For instance, Expert 3 placed a higher emphasis on the criterion of *partnership* relative to other experts, and Expert 2 weighed the BCR more heavily while assigning less importance to *quality of life is respected*.

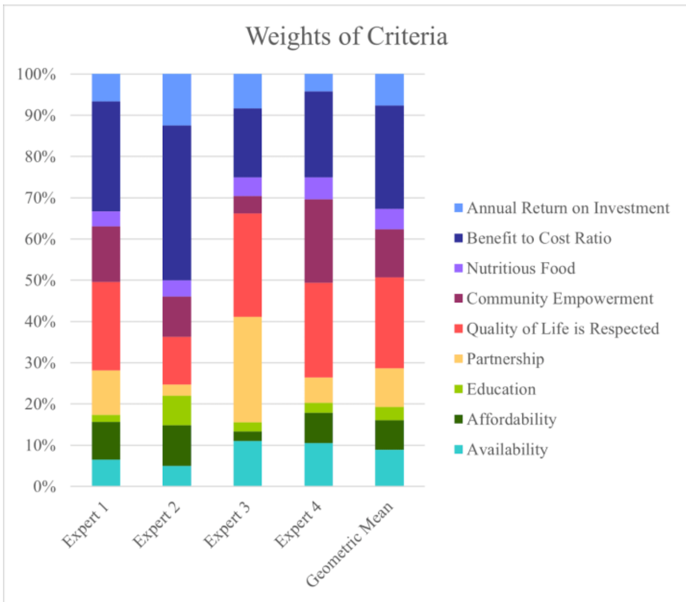

Figure 6: The assigned importance weights for the monetary and non-monetary criteria by experts and their geometric mean.

Despite these individual differences, the aggregate effect of their varied perceptions largely aligned with the outcomes derived from the geometric mean approach, leading to a consistent ranking of candidate alternatives. According to Figure 7, the singular deviation was noted with Expert 3's weights, where the healthy convenience stores, although scoring higher overall, were ranked below the Bus Shelter alternative.

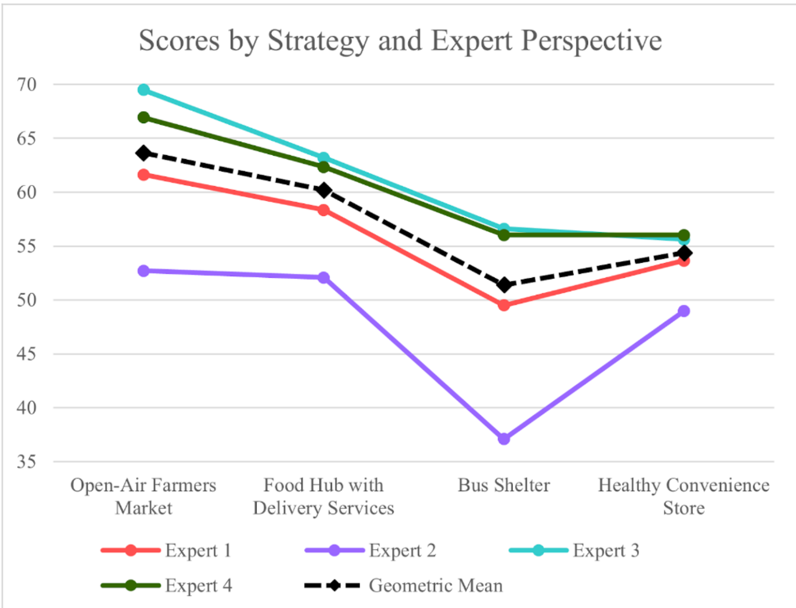

Figure 7: Final scores for the candidate alternatives based on the experts' importance weights and their geometric mean of their importance weights.

This variation underscores the crucial role of expert judgment in strategy evaluation and highlights how differing valuations of criteria importance can influence the final decision-making process. Such insights reinforce the necessity of incorporating diverse expert opinions to ensure a comprehensive assessment of strategies, which is fundamental for resilience planning.

5.5.3 Uncertainty analysis — worst-case, mean-case, and best-case scenarios

In BCA, variations associated with input data (benefits, costs, and externalities) are another source of uncertainty that should be considered in resiliency planning. Figure 8 illustrates the final scores of four alternatives under three different scenarios: worst case, mean case, and best case. For each scenario, the graph depicts a range of potential final scores, indicated by the upper and lower bounds.

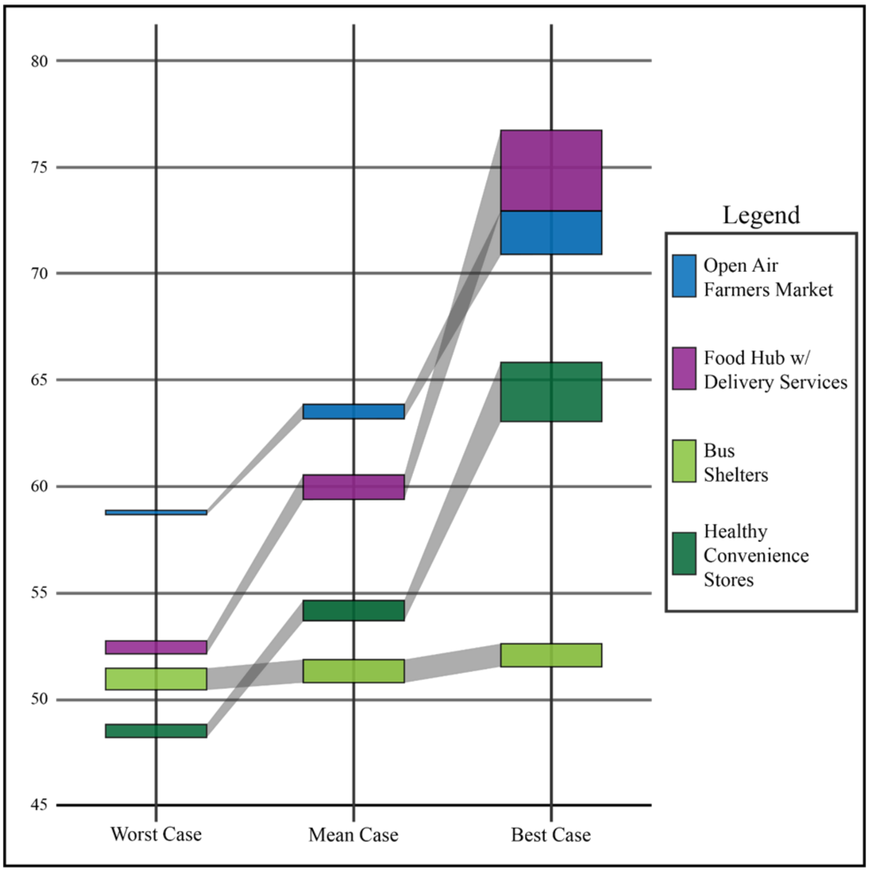

Figure 8: Comparison final scores for the candidate alternatives under worst-case, mean-case, and best-case scenarios.

These bounds demonstrate the variability in final scores due to the differing combinations of DR and PH, as explained in Section 4.2. Inherent uncertainty in the costs, benefits, and externalities significantly affects both the final scores and the subsequent ranking of the alternatives. Regarding the COVID-19 alternatives, the open-air farmers market holds the highest final scores, suggesting it is the preferable option under worst-case and mean-case scenarios. However, in the best-case scenario, the food hub with delivery services surpasses the open-air farmers market, indicating its potential to yield the greatest final scores under optimal conditions. Conversely, between alternatives of extreme weather events, the healthy convenience store is the most favorable alternative for the mean-case and best-case scenarios. Yet, in the worst-case scenario, the bus shelter emerges as the better option.

Among all the alternatives, the food hub with delivery services alternative exhibited the highest variation in final scores across scenarios, signifying heightened uncertainty. Conversely, the bus shelter alternative demonstrated minimal changes in final scores, indicating greater stability. This divergence may stem from the fact that the bus shelter is an infrastructure enhancement, whereas the other three alternatives are business models vulnerable to fluctuations in product supplies and customer demands. Moreover, the analysis revealed that uncertainty in costs, benefits, and externalities had a greater impact on final scores compared to DR/PH or variation in importance weights, underscoring the importance of carefully considering these factors in decision-making.

6. Discussion

The results elucidate the complexity of assessing resilience planning alternatives, illustrating how trade-offs between monetary benefits and non-monetary values shape decision-making. The model outputs highlight the variability in final scores based on different expert perspectives and the uncertainty inherent in input data, which can significantly influence the rankings of alternatives. This complexity underscores the importance of a nuanced approach to resilience planning that accounts for both quantifiable economic impacts and qualitative aspects like CIVs.

The findings of this study highlighted a few implications for Flint's food system resilience planning, particularly in addressing the impacts of the COVID-19 pandemic and extreme weather events. The monetary and non-monetary losses — as described in Sections 5.1.1 to 5.1.4 — underscore the vulnerabilities within Flint's food systems. These disruptions exacerbated food insecurity, emphasizing the need for targeted interventions to enhance Flint's food system. Moreover, the study reveals critical trade-offs between monetary and non-monetary dimensions in evaluating resilience strategies. Alternatives like the enhancement of bus shelters scored better in non-monetary aspects but underperformed in monetary terms. On the other hand, alternatives like food hubs with delivery services performed better monetarily but were not the best option when considering non-monetary criteria. These trade-offs demonstrate the importance of integrating community-identified values into resilience planning in food systems. The discussed potential shocks to Flint's food system emphasize the need for robust infrastructure and community-centered policies, which can be effectively evaluated using the Co-DECIDR approach to balance economic feasibility with CIVs.

As demonstrated through the proof-of-concept examples, the Co-DECIDR modeling approach enhances resilience assessment frameworks by incorporating three publicly available online modeling tools, each adding unique value to understanding and planning for resilience in the SES. Mental Modeler (Gray et al., 2013a) was employed to capture the diverse mental models of stakeholders, facilitating an understanding of the complex dynamics within the SES. EDGe$ (Helgeson et al., 2017) provided a robust modeling technique for the economic assessment of resilience planning alternatives. AHP-OS (Goepel et al., 2018) was instrumental in capturing expert perceptions to determine crucial importance weights for trade-off analysis. This integration offers a comprehensive and effective approach for community-based resilience planning across various SES, considering both monetary and non-monetary aspects, thereby broadening the scope of BCA and enhancing the applicability and effectiveness of resilience planning. Moreover, incorporating these tools aligns with GMP, ensuring model fitness for purpose by prioritizing usability, reliability, and feasibility, thereby meeting end-user needs through an accessible and practical resilience planning toolset (Hamilton et al., 2022).

The involvement of community members throughout the four-step Co-DECIDR process—from system understanding and shock impact analysis to alternative selection, evaluation, and trade-off analysis — embodies GMP (Gray et al., 2018; Wentworth et al., 2024). This approach aligns with the principles of participatory ensemble modeling as outlined by Schmitt-Olabisi et al. (2020), emphasizing legitimacy, parsimony, and practicality. Such engagement in understanding the system's behavior, identifying the impacts of shocks on the system, selecting and evaluating candidate alternatives, and conducting trade-off analysis ensures the representation of diverse community voices and values in resiliency planning (Legitimacy). Furthermore, it maintains model transparency and accessibility through Co-DECIDR's four steps (Parsimony), and addresses uncertainties in both process and outcomes with user-friendly modeling tools (Practicality). This community engagement not only fosters community trust and equity but also enhances the strength of resilience planning by understanding what the community members value, ensuring a comprehensive and effective response to systemic shocks.

Although the engagement of stakeholders and experts is crucial for the participatory modeling of SES and resilience planning, careful consideration must be given to who is included (Stringer et al., 2006). The sensitivity analysis revealed that diverse expert perceptions in assigning importance weights can alter the outcomes and rankings of alternatives. Engaging various stakeholder groups in FCM can produce different CI models, each reflecting unique system interactions. Therefore, a meticulous selection of stakeholders and experts covering a wide range of perspectives is essential in the Co-DECIDR modeling approach and resilience planning. This deliberate inclusion not only ensures the reliability of modeling outcomes but also captures a comprehensive understanding of system interactions, potential responses to shocks, and the valuation of criteria and their significance.

7. Limitations and future research

In our study, we utilized two straightforward proof-of-concept examples to demonstrate the Co-DECIDR application, focusing on a preliminary evaluation of candidate alternatives. The inherent limitations of this evaluation — particularly regarding the depth of the BCA and the strong reliance on assumptions due to data unavailability — underscore the need for more comprehensive evaluations in future work. The study's reliance on a limited number of interviews for determining importance weights presents another limitation. Increasing the number of interviews could enhance the reliability of these weights, ensuring they more accurately reflect community priorities and contribute to more robust decision-making processes.

One limitation of our study was the reliance on previously collected data, which was not initially gathered with the intent of analyzing shocks like COVID-19 or extreme weather, nor the potential alternatives for the Co-DECIDR project. While we adapted the existing collective intelligence model to evaluate these shocks and alternatives within our proof-of-concept examples, this approach may not fully capture the structural changes induced by such complex or severe shocks. Recognizing this limitation, we recommend that future studies purposefully collect data explicitly addressing various shocks and alternatives, particularly during interviews for individual fuzzy cognitive mapping. This approach would enable a more accurate representation and analysis of how these factors might structurally alter system dynamics, enhancing the robustness and applicability of the Co-DECIDR model.

To address uncertainties related to benefits, costs, and externalities in BCA, we defined best-case, mean-case, and worst-case scenarios to determine the monetary and final scores. Future research can, however, leverage the advanced probabilistic capabilities of Monte Carlo simulations available within the EDGe$ package for a more nuanced analysis of uncertainties in BCA inputs. Monte Carlo simulations are instrumental in encapsulating the spectrum of uncertainties impacting resilience planning and the outcomes of various scenarios (Kannan et al., 2021; Mavrotas & Makryvelios, 2021). By employing Monte Carlo simulations, the robustness of models can be enhanced, facilitating a more comprehensive evaluation of resilience strategies within the dynamic and uncertain conditions that characterize the SES.

Future expansions of Co-DECIDR could benefit from incorporating Life Cycle Assessment (LCA) to evaluate the environmental impacts of candidate alternatives more thoroughly and effectively (De Luca et al., 2017). Utilizing a publicly available, user-friendly modeling tool for LCA, such as openLCA (Ciroth et al., 2014), would enable a more holistic understanding of the ecological consequences of resilience planning strategies, aligning with sustainability goals. LCA can be integrated with FCM models and BCA models to more comprehensively cover the social, environmental, and economic dimensions of resiliency strategies and facilitate trade-offs and multi-criteria analysis.

8. Conclusion and next steps

Earlier sections illustrated how Co-DECIDR effectively combines the qualitative insights of FCM with the quantitative rigor of BCA and determines the ranking of candidate alternatives through trade-off analysis. This integration allows planners to more clearly and effectively address the complexities of SES. In applying the Co-DECIDR modeling approach to the Flint food system, our focus was on addressing two main types of shocks: pandemics like COVID-19 and extreme weather events. This comprehensive approach encompassed both monetary and non-monetary criteria to assess candidate alternatives for resilience planning. Utilizing tools like the EDGe$ online tool (Helgeson et al., 2017; Helgeson & O'Fallon, 2021) and Mental Modeler (Gray et al., 2013a) enabled us to analyze the benefit-cost ratio and return on investment of potential strategies, while also exploring how CIVs crucial for the ongoing resilience planning of the Flint food system might be affected. It also sets the boundaries on which options are considered viable for the community.

The application of Co-DECIDR yielded significant insights into the trade-offs between monetary and non-monetary criteria, emphasizing the importance of CIVs in resilience planning. By incorporating MCDA (Abdullah et al., 2021), we were able to identify the most suitable resilience strategies based on community priorities, ensuring a process that was equitable, cost-effective, and inclusive. This approach, grounded in the engagement of community representatives throughout all steps of the Co-DECIDR process, underscores its potential for yielding more equitable solutions than BCA methods alone.

The Co-DECIDR modeling approach notably advances GMP in the resilience planning of SES and offers a leading practice approach that addresses several limitations of BCA alone. By integrating economic models with participatory modeling techniques, and by embodying principles such as addressing model feasibility and reliability, as well as ensuring stakeholder engagement throughout the modeling process, Co-DECIDR sets a new benchmark for modeling practices in resilience planning. This approach engages stakeholders in a manner that aligns with GMP by promoting inclusiveness, transparency, and robust decision-making under uncertainty. Specifically, the participatory aspect of Co-DECIDR, facilitated through tools like Mental Modeler, fosters a shared understanding of the system under study, ensuring that the modeling process is comprehensive and grounded in community-identified values and priorities. This guarantees that the models are not only technically sound but also socially relevant and accepted. Thus, Co-DECIDR addresses critical aspects of GMP such as meaningful engagement of end-users, systematic elicitation of stakeholder needs, and fostering transparency and traceability in model development. Moreover, by integrating qualitative and quantitative methods, Co-DECIDR effectively navigates the complexities and feedback loops within SES, offering an evaluation of resilience strategies that are reflective of diverse community needs. This alignment with GMP enhances the model's applicability, relevance, and the quality of decision support it provides for resilience planning.

Furthermore, the flexibility in Co-DECIDR steps allows for broad application across decision making contexts and decision topics. Demonstrated by the proof-of-concept examples described in this paper, Co-DECIDR's integration of economic modeling with participatory techniques offers valuable perspectives for other socio-ecological systems facing diverse shocks, ranging from wildfire management in forestry systems (McWethy et al., 2019) to water scarcity adaptations in regions affected by climate change (Roach et al., 2018). This adaptability highlights Co-DECIDR's capacity to inform resilience planning across various contexts and scales, making it a proper modeling approach for addressing complex social, economic, and environmental challenges.

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Supplementary Material

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