Using Participatory Modeling to Understand and Manage Complex Adaptive Systems

by

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Dedication

To the people of Flint, Michigan. Thank you for honoring me with your knowledge.

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Abstract

"Wicked" problems like climate change, food insecurity, and poverty are difficult to understand and manage, as the socio-environmental systems that produce them are rife with uncertainty, complexity, and counterintuitive dynamics. We are often faced with the reality of making important decisions in data-sparse environments while balancing trade-offs and stakeholders with different, and frequently conflicting, priorities. This dissertation studies how community-engaged research, and more specifically semi-quantitative participatory modeling, can be used to center local knowledge, explicitly address trade-offs, and develop place-based interventions towards sustainability and justice.

Chapter 2 utilizes a systematic literature review to ground a holistic understanding of the sustainability outcomes of the US food system. This research found trends like an overrepresentation of environmental outcomes and lower inclusion of social outcomes in articles published by natural science journals.

Chapter 3 tests methods of aggregating diverse local knowledge into an accurate and parsimonious representation of a complex system using a case study of the Flint, Michigan food system. We found that aggregating by identity groups serves as a poor proxy for cognitive diversity in a system where knowledge and expertise can arise from many sources.

Chapter 4 focuses on synthesizing and evaluating interventions towards racial equity in the Flint, MI food system. This research resulted in recommendations to provision resources towards Black, Indigenous, and people of color (BIPOC) business owners and entrepreneurs, as

well as lowering racialized barriers to affordability and availability to enable community members to participate in the localized food system.

Finally, we conclude by exploring how transdisciplinary computational social science can be applied in complex adaptive systems to promote transparent and effective decision-making.

Chapter 1 Introduction

Sustainability science is a young field. It stands, amongst its grey-haired peers like physics, mathematics, and theology, as an awkward teenager – still figuring itself out. Sustainable development as a concept emerged in the 1970s and 1980s, spurred on by documents like the 1987 United Nations Brundtland report, Our Common Future (Brundtland, 1987), to gain widespread traction through the 1990s (Gatto, 1995). Bettencourt and Kaur assert that, based on collaboration and coauthorship networks, the field of sustainability science unified around the year 2000 (Bettencourt & Kaur, 2011). When comparing sustainability science to Sumerian accounting in 3000 BC, or to the philosophies developed by Plato in ancient Greece, it may even be more proper to say it is in its infancy.

Foundationally, sustainability science is an interdisciplinary field motivated by real-world problem-solving. Important sustainability challenges like climate change and food insecurity are "wicked problems" in that they are difficult to understand – due to traits like multi-scalar interconnections and high levels of uncertainty – and that they have no definitive solutions, because of distributed power, diverse interests, and implicit tradeoffs between approaches (Rittel & Webber, 1974). Addressing these sustainability challenges requires the utilization of multiple academic disciplines, taking a systems lens, and engaging with stakeholders to accurately capture the complex interactions between social and natural systems and combine diverse perspectives to guide sustainable transformation (Clark & Dickson, 2003; Kates et al., 2001). In this chapter, I will contextualize three core aspects of sustainability research: 1) interdisciplinarity, 2) systems approaches, and 3) transdisciplinarity, as the basis of my research on participatory modeling in complex adaptive socio-environmental systems. Finally, I will provide an overview of the specific participatory modeling methodology, fuzzy cognitive mapping, used in my work and ground this approach in constructivist psychological theory.

1.1 Interdisciplinarity

The term "interdisciplinary" was first used in the social sciences in the mid-1920s, but only gained broader use post-World War II (Moran, 2010). In the late 1960s and 1970s, interdisciplinarity was considered in educational reform due to rising critiques of the rigid division of disciplines and specialization in science, as well as the need for students to be able to handle the increasing complexity of a globalized world (Newell, 2010; Weingart, 2000). These two approaches to science – disciplinarity and interdisciplinarity – were seen to be at odds. Thomas Kuhn called this "the essential tension" between "normal research" that conducted basic science that uses convergent thinking and interdisciplinarity that utilizes divergent thinking to reject norms and pursue new directions (Kuhn, 1977). Through a historical lens on the evolution of science, Kuhn posited that significant scientific revolutions require divergent thinking, flexibility, and open-mindedness.

Interdisciplinarity is often linked to *innovation* because it lowers communication barriers between disciplines, encourages applying theories and methods in new contexts, provides outsider perspectives on an issue, and facilitates the creative amalgamation of ideas (Nissani, 1997). Environmental science, as a combination of fields like biology, chemistry, and physical sciences, is better suited to addressing environmental problems than the singular disciplines from which it draws. Similarly, sustainability science coalesced from a variety of disciplines to harness distributed knowledge in order to address unique problems and enact societal change (Jerneck et al., 2011; Matson et al., 2016).

1.2 Systems Approaches

The socio-environmental systems that create sustainability challenges are complex adaptive, which means that they are comprised of many interacting elements that can have non-linear relationships, heterogeneous goals, multi-scalar dynamics, as well as the ability to change, react, and learn (Holland, 2006; Lansing, 2003). One particularly difficult aspect of complex adaptive systems is emergent behavior – where dynamics emerge from interactions of elements that cannot be determined by studying the elements in isolation (Holland, 1992). A classic example is the flocking behaviors of birds.

Emergent behavior lends credence to the emphasis in sustainability work on both systems approaches and system modeling, but it also touches on a fundamental division in science: reductionism versus holism. Reductionism versus holism is an epistemological split; either an entity can be studied through the aggregation of small, cumulative parts (reductionism), or a broader perspective must be taken because the whole is not a sum of its parts (holism) (Andersen, 2001; Verschuren, 2001). Holism, the idea that component interrelationships influence system behavior, is a foundational aspect of systems approaches. However, there have long been academic debates if reductionism can capture emergence (Wimsatt, 1997).

In Herbert Simon's seminal paper, "The Architecture of Complexity," he posits that reductionism can be used to study emergence because complex systems are hierarchical and can be decomposed into subsystems that can be more easily understood. He stated that if "there are important systems in the world that are complex without being hierarchic, they may to a considerable extent escape our observation and our understanding. Analysis of their behavior would involve such detailed knowledge and calculation of the interactions of their elementary parts that it would be beyond our capacities of memory or computation" (Simon, 1962). Simon's paper was published in an era when computers were expensive, large machines used mainly for research. For context, computing advances around this time were early applications of graphical user interfaces, which were controlled with light-pens instead of the now-ubiquitous mouse (Sutherland, 1963). Modern technology enables the parameterization and simulation of hundreds of thousands of interrelated concepts.

Despite the focus of this dissertation on holistic systems approaches, it is important to recognize the role of reductionism in science. The scientific revolution of the 16th and 17th centuries is hallmarked by now-ubiquitous ideas like the scientific method, heliocentrism, and gravity. Science of yore was focused on understanding the fundamental laws that governed nature, using novel technologies like the microscope and the telescope; scientific disciplines became specialized and solidified through the process of categorizing knowledge, which reduced replication and, when combined with a reductionist perspective, enabled large advances in knowledge (Moran, 2010).

However, the globalized and complex nature of modern socio-environmental systems require systems approaches, which has motivated the uptake of practices like systems thinking and modeling in sustainability work. To quote Donella Meadows, a leader in systems thinking,

> "[o]nce we see the relationship between structure and behavior, we can begin to understand how systems work, what makes them produce poor results, and how to shift them into better behavior patterns. As our world continues to change rapidly and become more complex, systems thinking will help us manage, adapt, and see the wide range of choices we have before us," (Meadows, 2008).

The field of system dynamics originated in the 1960s from engineer and systems scientist Jay Forrester's work on computer models for industrial systems and urban dynamics (Forrester, 1969). Models are simplifications of reality that allow people to explore systems and gain insights from observations that are potentially too complex to hold in our minds. Humans have cognitive limitations for understanding complex systems, particularly when compared to computers (Doyle, 1997; Miller, 1956; Simon, 1957). Systems approaches to research, particularly computer-aided system modeling, have enabled researchers and practitioners to understand how systems work, to increase the size and scope of systems under study, to anticipate consequences and avoid unintended consequences, and to identify where interventions will have the greatest impact.

1.3 Transdisciplinarity

While a single definition of transdisciplinarity is still being consolidated in academic literature, it is generally considered an integration of disciplinary methodology and collaboration across researchers and stakeholders to solve complex problems (Brandt et al., 2013; Wickson et al., 2006). This intentional involvement of stakeholders in the research process, via approaches like community-engaged or participatory research, is a critical element of transdisciplinarity (Balsiger, 2004; Horlick-Jones & Sime, 2004). Active input from stakeholders and engagement with knowledge production is particularly relevant for sustainability work that aims to both integrate local preferences into decision-making processes and close the research-practice gap to effectively implement change (Hirsch Hadorn et al., 2006). Optimally, transdisciplinary sustainability research would include collaboration and co-production between researchers and stakeholders from the early stages of problem-structuring through to the final application of new knowledge into practice (Lang et al., 2012).

Participatory approaches – where collaborations between researchers and stakeholders are equitable, diverse sources of experience are valued, and knowledge is co-constructed – can be invaluable to just and sustainable transformations (Bennett et al., 2019; Scoones et al., 2020). Yet, the proliferation of transdisciplinary work must overcome 1) the lack of standardized methodological tools and research frameworks inherent in developing interdisciplinary spaces, as well as 2) the intrinsic difficulties of working towards equitable community empowerment and real-world impact (Brandt et al., 2013). Ethical community engagement must be centered, particularly given the history of extractive academic research. Community-based participatory research can be powerful, but it must be undertaken with genuine commitment to equitable engagement, transparency, honest communication, established feedback mechanisms, and awareness of power dynamics (Balazs & Morello-Frosch, 2013; Mikesell et al., 2013).

1.4 Participatory Modeling

Enabled by technological advancements in the digital age, computational social science is an emerging interdisciplinary field that utilizes computational methods to understand social systems and behavior (Edelmann et al., 2020). The reality of sustainability work is that people are often forced to make important choices about complex systems with high uncertainty and low data availability. One common computational social science method is simulation models, which can be powerful tools to evaluate alternative policies and test the sensitivity of parameters (Cioffi-Revilla, 2010). A key goal of my doctoral research is to expand methodological tools to reduce uncertainty about complex systems and support transparent and effective decision-making that promotes sustainability and justice.

John Sterman, a systems scientist, argues that,

> "successful approaches to learning about complex dynamic systems require (1) tools to articulate and frame issues, elicit knowledge and beliefs, and create maps of the feedback structure of an issue from that knowledge; (2) formal models and simulation methods to assess the dynamics of those maps, test new policies, and practice new skills; and (3) methods to sharpen scientific reasoning skills, improve group processes, and overcome defensive routines for individuals and teams" (Sterman, 1994).

I propose that participatory modeling can address most, if not all, of these requirements.

Participatory methods have been used to balance scientific inputs and value-based inputs. This is important for high quality decision making, particularly in complex and uncertain socio-environmental systems (Failing et al., 2004). To make perfectly optimal decisions, we would need to know everything about a system's components, dynamics, and exactly how our actions impact system behavior. This is possible in simple systems. Imagine a game of virtual pool, where a computer knows all the rules of the game and the physics of the table; it could easily calculate the exact angle and velocity to hit the cue ball to make the most strategic play. This is essentially impossible in complex adaptive systems like the food system because of 1) the innumerability of the components and their interrelationships and 2) the subjectiveness of what is "the most strategic play." Instead, we must strive to make decisions using the best available information and socially negotiate the prioritization of outcomes and management of tradeoffs. This is a key motivation of participatory modeling.

Participatory modeling, as defined by Voinov et al., is "a purposeful learning process for action that engages the implicit and explicit knowledge of stakeholders to create formalized and shared representations of reality" (Voinov et al., 2018). The linking of participatory procedures with system modeling enables the integration of stakeholder/expert knowledge into models that can be used to understand complex systems and guide collective decision-making (Jones et al., 2009). Use of expert judgement and stakeholder values in environmental decision-making has a long history, as these can be used to structure problems and explicitly evaluate alternatives based on people's preferences (Failing et al., 2004; Gregory et al., 2012). Meaningful involvement of the public with research and decision-making processes can increase the quality and acceptability of choices (Gregory, 2000). The process of facilitated participatory modeling can also promote social learning that positively impacts community resilience and adaptive capacity (Henly-Shepard et al., 2015). Participatory modeling can utilize different modeling tools, each with trade-offs.

1.4.1 The Math Behind FCM

From a methodological perspective, fuzzy cognitive maps are semi-quantitative models where participants create causal connections (edges) between concepts (nodes). The "fuzzy" aspect of fuzzy cognitive mapping comes from the use of fuzzy logic for connection strength; as opposed to Boolean logic where connections either exist (1) or do not (0), connections in FCM's can range from zero to one, which can better capture the complexity and uncertainty of reality (Aguilar, 2005; Kosko, 1986).

When working with people, FCMs are often graphically represented in node-and-link diagrams, but they are mathematically adjacency matrices ($\mathbf{W}_{NxN}$, where N is the total number of nodes). The weighted nature of FCMs means that "what if?" scenario analysis can be performed, where an activation vector ($\mathbf{A}^{(t)}$) is used to iterate the matrix until convergence is reached (Nápoles & Giabbanelli, 2024; Papageorgiou & Salmeron, 2013), as shown below

$$A^{(t+1)} = A^{(t)} \cdot W = f\left(\sum_{j=1}^{N} a_j^{(t)} * w_{j,i}\right)$$

where f is a threshold function that squashes data into a set interval. For example, a prominent threshold function is the hyperbolic tangent function

$$f(x) = tanh\,(x)$$

which maintains an interval of [-1,1] (Stylios & Groumpos, 2004). This process can be useful for exploring system dynamics and testing interventions (Gray et al., 2015; Mourhir, 2020). While FCMs can neither manage complex dynamics like non-linear relationships nor model spatial or temporal dynamics, the high ease of use with stakeholders can be well worth the tradeoff of analytical capability.

1.4.2 The Theory Behind FCM

Cognitive mapping, upon which FCM is based, was developed by political scientist Robert Axelrod in 1976 as a way to map and model social and political systems (Aguilar, 2005; Kosko, 1986). The basic premise is that peoples' knowledge and understanding of complex systems can be turned into a model which can be used in a variety of research applications from cognitive science, decision-making, psychology, systems science, or sustainability science. While I am a methodologist and not a philosopher, it is necessary to take a large step back and consider how FCM draws from some of the foundational theories of knowledge – starting with *positivism*.

The history of science, as discussed in previous sections, is integral to explaining past and present trends. There is a long tradition of establishing divisions and hierarchies among academic disciplines, particularly by philosophers like Aristotle, René Descartes and Immanuel Kant (Moran, 2010). As the social sciences developed in the late 18th and early 19th centuries, scholars in the 'human sciences' worked to garner legitimacy in the larger scientific community. Auguste

Comte, who is credited with popularizing “sociology” in the 1830s, advocated for the application of rigorous scientific methods to the social sciences and humanities (Moran, 2010). Comte’s work gave rise to the *positivism* movement which aimed to empirically test social theories (Turner, 2001). Positivists generally believe that there are universal laws that govern social systems, just as there a laws like gravity or heat conduction that govern natural systems. Positivist methodologies lean towards quantitative or statistical analysis, while *non-positivists* utilize more ethnographic approaches as they do not believe that there are universal truths about humans and social systems.

Constructivism, expanded by the work of scholars like Jean Piaget and Lev Vygotsky, is a *non-positivist theory of learning* that stems from cognitive science and biology research seeking to understand cognitive processes, learning, and evolution (Fosnot & Perry, 1996). In short, the theory is that humans construct mental systems by organizing and classifying experiences and knowledge about the world around them. Constructivists view humans as active participants, rather than passive reactors, to the process of learning and meaning-making (Mahoney, 1988). Research on how people process reality into systems of symbols is present in fields like cognitive science, neuroscience, and artificial intelligence (Barsalou, 1999; Chiari & Nuzzo, 1996; Vera & Simon, 1993). FCM, however, is grounded in is *constructivist psychology* (Gray et al., 2014; Voinov et al., 2018).

Constructivist psychologists study how humans create cognitive systems in order to inform psychotherapy practices (Raskin, 2002). Consider George Kelly’s highly influential Personal Construct Theory (PCT), that people are constantly creating hypotheses and models about the world that are refined through experience, and that these personal constructs can be used for psychological evaluation (Kelly, 1955). FCM draws from both the theory of how the external world influences the construction of internal, subjective realities (and vice versa) and the practice of studying personal constructions.

These internal constructions of the world, also called mental models or cognitive maps, are significant because people use them to make sense of reality and make decisions (Craik, 1952). Through the modeling process, we can externalize knowledge and perception into dynamic, weighted graphs which can then be studied (Doyle & Ford, 1998; Stylios & Groumpos, 2004). FCM is a methodological tool, so if an application aims to understand individual perception, then directly translating an internal construct is well-suited to the research goal. However, if the goal is to approximate a complex socio-environmental system through expert and/or local knowledge, a fundamental question is sparked: *how do we know if the knowledge is accurate?*

Attempting to answer this question begins with a more existential one: does external reality exist? Constructivism draws on both sides of the ontological debate about the relationship between reality and knowledge - *realism* versus *idealism* (Mahoney, 1988). The differences between these two perspectives can be exemplified through the classic philosophical thought experiment of 'if a tree falls in a forest and no one is around to hear it, does it make a sound?' A realist would answer yes, as they believe that external reality exists independently from humans. An idealist would answer no, because they view reality as something that is dependent on our consciousness and experience. Constructivists may take the hybrid perspective of *limited realism*, where an external reality exists and it is possible to know that reality, but the correlation between knowledge and reality is imperfect because of fallible human perception (Chiari & Nuzzo, 1996). Humans are simultaneously excellent at recognizing patterns and limited by our brains' capacity to manage complexity - we simplify reality into mental models, have bounded rationality, and use cognitive shortcuts like decision heuristics (Arthur, 1994; Simon, 1957).

In participatory modeling, we take the constructivist perspective of limited realism and assert that experiential knowledge can accurately reflect reality, but researchers and practitioners must be conscious of cognitive limitations and bias. Fuzzy cognitive mapping as a participatory modeling tool is generally either conducted through individual interviews or in a workshop setting with groups of participants. In group settings, facilitators need to manage negative group dynamics, but these can be productive spaces for co-learning, collaboration, and critical thinking that can inform decision-making (Gray et al., 2014; Singer et al., 2017).

Multiple individual FCMs can also be aggregated together into a collective intelligence model, which can represent a more holistic perspective of the system under study and reduce individual biases (Aminpour et al., 2021; Gray et al., 2012). The benefits of aggregation emerge from "wisdom of the crowd" and collective intelligence theories – the idea that a combination of people's varying experiences and perspectives can accurately approximate real-world systems (Aminpour et al., 2020; Gray et al., 2020). Creating generalized constructions can encourage social negotiation, communication, and understanding of how other people's perspectives, as well as presenting an opportunity for reflection on your own perception of the world (Fosnot & Perry, 1996). Utilization of local and/or expert knowledge through FCM has been used in broad socio-environmental contexts to deepen system understanding, facilitate social learning, and inform transparent decision-making (Gray et al., 2012; Gray et al., 2014; Papageorgiou & Kontogianni, 2012).

1.5 Dissertation Overview

In this dissertation, I present three studies that utilize interdisciplinary, systems approaches to deepen understanding of my research context: sustainable food systems. Afterwards, I develop a parsimonious system model based on local expertise and synthesize interventions for sustainable transformation. Chapter 2 is a systematic literature review to develop a holistic inventory of the sustainability outcomes of the United States food system. The aim of this literature review is to synthesize across disciplines to establish an expansive list of potential outcomes to consider for sustainability evaluations within the food system, as well as to identify trends across food systems literature. Early sustainability discourse centered on topics like consumption, environmental disasters, and critiques of economic development. Over time, these discourses evolved into variations of the "three-pillar" or "three-legged stool" model of social, environmental, and economic sustainability (Purvis et al., 2019). However, the three dimensions have historically not been treated equally – with more emphasis placed on ecological systems (Littig & Griessler, 2005). I found that environmental outcomes were prominently represented, while social outcomes were less frequently included – particularly by articles published by natural science journals.

This conceptual grounding is essential to Chapters 3 and 4 where I investigate the Flint, Michigan food system through participatory modeling to develop a collective intelligence model based on localized knowledge, perspectives, and beliefs. In Chapter 3, I specifically focus on how different sources of food in Flint (retail, emergency sector, and supplemental nutrition programs) impact community-defined food system values. Through semi-structured interviews with local food system experts, I modeled individual perspectives and knowledge of the food system and evaluated two different methods for aggregation into a collective intelligence model:

aggregating by identity diversity or by cognitive diversity. Both methods are used in FCM aggregation, but there is limited quantitative and qualitative comparison. I found that when participants have diverse sources of expertise and knowledge of the study system, aggregating by cognitive diversity produces a collective intelligence model that is both more accurate to expectations for a complex system model and experts' understanding of system dynamics. Aggregating using cognitive diversity is more resource-intensive, but ultimately produced a more parsimonious model that balanced visual simplicity and dynamic complexity.

Chapter 4 utilizes a different set of participatory modeling interviews that are focused on how racial inequity impacts participation in Flint's localized food system. As part of these interviews, I elicited participants' ideas for "leverage points" – actions that would create proportionately larger positive change in the food system. This chapter synthesizes and evaluates these ideas for interventions using causal mapping and archetype analysis to identify trends and insights from narrative data. I show that two main archetypes – "Success to the Successful" and "Shifting the Burden" – can be used to depict system dynamics, which, in turn, means that interventions should target inequitable distributions of resources and address the fundamental systemic causes of racial inequity rather than its symptoms. For example, allocating resources like capital, land, and job training to current and prospective Black, Indigenous, and people of color (BIPOC) business owners and entrepreneurs. Strengthening an equitable local food economy also requires making participation affordable and accessible for community members. In the final Chapter, I share additional conclusions from community-engaged research, propose research directions for participatory modeling, and discuss the future of sustainability science.

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Chapter 2 Sustainability Outcomes of the United States Food System: A Systematic Review[1]

2.1 Abstract

Food systems literature has shifted towards interdisciplinarity and the use of systems lenses but can still be disjointed and unconnected. To bring together disciplinary knowledge and establish a common understanding of food systems, we conducted a systematic review to inventory sustainability outcomes of the U.S. food system. The literature search returned 2,866 articles, which was reduced to 49, reviewed here. A qualitative content analysis process identified 93 outcomes. These were split across three main themes of environmental, socio-economic, and health outcomes. This review also identified several trends in food systems literature, such as an underrepresentation of socio-economic outcomes and a lack of inclusion of social outcomes in natural science journals. The sustainability outcomes inventoried here may help to facilitate greater communication and collaboration in food systems research and situate current and future food systems studies within this inventory.

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2.2 Introduction

It is difficult to underestimate the complexity of the food system. A single meal consists of individual ingredients with pathways from farm to fork that vary widely. Conceptualizations of food systems differ across disciplines and time, but recent definitions generally include the following: (1) processes or activities such as food production, processing, consumption, and disposal; (2) interactions among biogeophysical and human systems; and (3) environmental, socio-economic, and health outcomes (Béné et al., 2019a; Ericksen, 2008). Outcomes can be defined as the causal results of food system processes (Ericksen, 2008).

The term "food system" goes back several decades, but until more recently, most of the discussion was implicit or limited to a subsystem or a specific system element (Sobal et al., 1998). For example, agricultural and food security fields dominated early food systems literature and focused on topics such as production, distribution, consumption practices, or innovations that increased productivity and efficiency (Béné et al., 2019b; Reganold et al., 2011; Stephens et al., 2018). Much of the early conversation around sustainability focused on the environmental impacts of agriculture like soil erosion, climate change, or pollution (Béné et al., 2019b; Ericksen et al., 2009; Hallam et al., 1993; Hinrichs, 2012). Sustainability as a concept grew out of the two disconnected but parallel movements of environmental and social sustainability in the 1970s that critiqued capitalist economic growth (Purvis et al., 2019). The inclusion of health into the popularized, and criticized, "three pillars" or "three-legged stool" concept of social, economic, and environmental sustainability only began in the 1990s; it has gained prominence more recently and was accompanied by proponents of sustainable agriculture (Gillespie, 1995; Hancock, 1993; Purvis et al., 2019).

As an emerging field, writers of food systems literature aim to effectively incorporate multiple facets of sustainability through methods or lenses such as systems thinking and inter-/transdisciplinarity. However, a historical lack of interdisciplinarity in the food systems space, reflective of trends throughout scientific study, results in significant gaps in system understanding, theories, and methodologies (Béné et al., 2019a; Nelson et al., 2016a). For example, discussions of the impacts on health like income, social justice, and equity have become prevalent only more recently (Marmot, 2005; Solar & Irwin, 2006). Furthermore, much research that would fall within the food systems space (such as system aspects like agroecology or food science) retains a disciplinary focus and does not address the inherently interdisciplinary context of food systems (Béné et al., 2019a). These factors have resulted in food systems work that is fragmented and difficult to connect (Eakin et al., 2017; NRC, 2010;).

Food system scholars call for increasingly integrative and interdisciplinary research to fill the gaps by addressing the system's diverse, interacting elements and outcomes (Constance, 2010; Hinrichs, 2012; Nelson et al., 2016a). The authors of a literature review of food system drivers, defined in that review as processes that influence the food system durably and consistently, concluded that a collective understanding of food system elements and dynamics is underdeveloped and that establishing a common foundation of food system knowledge is important to better assist academics, experts, and decision-makers in the food systems space (Béné et al., 2019b). These gaps prompted the question: What are the prominent sustainability outcomes of the U.S. food system, and how does food systems literature address the diverse and interconnected issues?

Within the review, we provide a comprehensive inventory of recent scientific literature about how the U.S. food system results in sustainability outcomes. We identify, categorize, and calculate the frequency of sustainability outcomes of the U.S. food system that are reported in recent scientific literature to draw insights about interdisciplinarity and trends within food systems literature. Our goal is to advance food systems literature by compiling often disparate information about the sustainability outcomes and provide a holistic and accessible evaluation that could be used to inform or contextualize further food system work. For example, the inventory of outcomes could be the basis for developing interdisciplinary metrics for evaluating a community's food system. While information and shared understanding is only one aspect of successful collaboration and problem-solving, it is an initial step that is needed in the sustainable food systems space.

2.3 Methods

2.3.1 Reviewing the Literature

We use two main processes: (1) a systematic review to ensure a holistic information base, and (2) qualitative hand-coding to identify outcomes within the texts. The methods used were adapted from standard systematic review methodologies for formulating and conducting a search (Tsafnat et al., 2014; Uman, 2011). We developed search terms, performed the search, removed duplicate texts, and screened the remaining abstracts and full texts based on inclusion and exclusion criteria. Content analysis methods like qualitative hand-coding are effective ways to identify concepts in texts and are a common approach to revealing trends across and within bodies of literature (Berelson, 1952; Hsieh & Shannon, 2005; Weber, 1990). Hand-coding is when a researcher manually reviews data by identifying concepts and assigning a code, which is very time-intensive but results in more inclusive coding that can capture meaning that would be missed by computer programs (Grimmer & Stewart, 2013; Nelson et al., 2021; Weber, 1990). For more detailed information on the systematic review process and rationale for choosing these methodologies, see Appendix A.

2.3.2 Coding the Literature

We began the analysis process by copying the exact terminology or phrasing used in the texts to describe or identify sustainability outcomes to a Microsoft Excel file. We then simplified the exact phrasing into more abstract or generalized coding terms. For example, one text may discuss "pathogen contamination of food" while another uses "foodborne pathogen," both of which communicate the same outcome and would be grouped under the term "pathogen contamination of food." The code reduction and organization process sorted and refined the initial 191 outcomes into three overarching themes: environmental, socio-economic, and health outcomes. In each theme, outcomes were organized into categories and subcategories.

2.3.3 Organization of Outcomes

The organization of outcomes into themes, categories, and subcategories was based on common groupings or connections that emerged from the source literature. Thus, the organizational method used a 'grounded theory' approach, as the clustering of outcomes was developed from the data rather than fitting concepts into a preexisting or preestablished scheme (Glaser & Strauss, 1967). A primary goal of the organizational process was ensuring that each outcome could only be coded into one category (i.e., mutual exclusivity) (Weber, 1990). The final organization of codes and outcomes represents an inventory of the major themes and prominence of outcomes based on how often they occur in the reviewed literature. Expanding or excluding outcome categories could deepen or streamline the process depending on the field or focus of work.

2.4 Results

The database search resulted in the collection of 2,866 articles, which was reduced to 75 based on the titles and abstracts using the remaining inclusion and exclusion criteria. At the full text review stage, 26 additional articles were excluded (see Figure 2-1 and Appendix D for a full list of reviewed documents). Common reasons for exclusion were focusing at the wrong scope (n=7) or on one specific sustainability issue (n=8). Other reasons include papers focusing on methodologies or recommending metrics (n=4) or papers that simply did not address the research question of this review (n=3). The publishing dates ranged from 1993 to 2019, with the majority published after 2013.

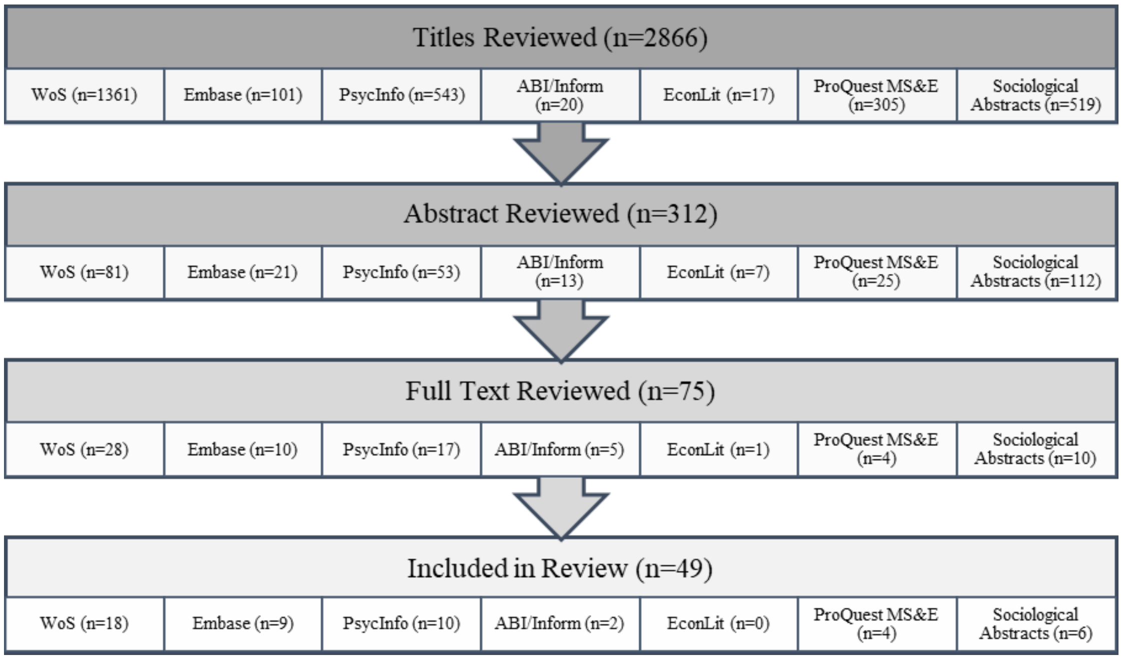

Figure 2-1: Flow chart of articles resulting from systematic review process.

The initial round of coding resulted in 1,074 instances of coding, which identified 191 outcomes. In this first step, the articles had an average of 16.7 outcomes, with a range of three to 56 outcomes. The prevalence of outcomes also varied, with greenhouse gas emissions and water quality being present in 22 articles, while 51 of the outcomes were only in one article. This list of outcomes was then narrowed by compiling redundant codes and simplifying longer phrases. For example, "unsafe working conditions" and "dangerous working conditions" were combined. Each outcome was then organized into the hierarchical structure of categories, subcategories, and specific outcomes (see Table 2-1).

Table 2-1 Outcome Organization Structure with Definitions + Examples

Definitions:	**Examples:**
Theme: highest level of organization, contains the three main themes	Environmental Outcomes
Category: concepts generally encompass many outcomes or cannot be sorted into another category	Environmental Pollution

Subcategory: used when helpful to group similar outcomes within categories	Air Pollution
Specific Outcome: All outcomes within subcategories	Greenhouse Gas Emissions

This second step resulted in the organization of 93 outcomes into three main themes: environmental, socio-economic, and human health outcomes (see Figure 2-2). The average number of codes per outcome is 10.24, but there was variation among the themes. The number of articles per outcome, or density of codes, indicates how prevalent an outcome was in the literature. The environmental outcomes theme had the highest average density of codes per outcome with 11.8, with the health outcomes and socio-environmental outcomes themes having 10.3 and 8.75 codes per outcome, respectively. A detailed explanation of each outcome identified, summarized from the reviewed literature, is in Appendix B. This breakdown can be useful as an interdisciplinary introduction to the diversity of sustainability outcomes of the food system. For raw coding results, see Appendix C.

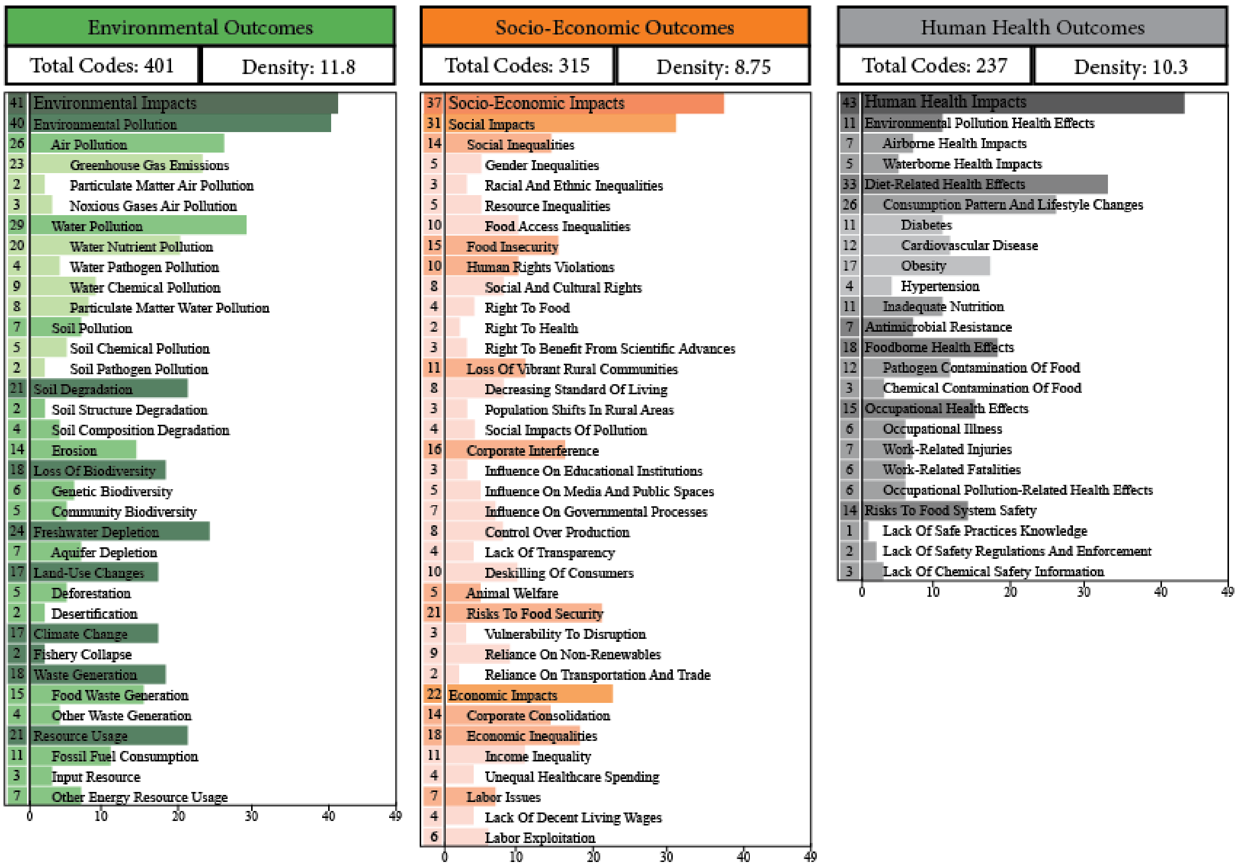

Figure 2-2: Organization of outcomes identified by systematic review, including number of coding instances. Coding frequency is represented as a bar graph, with the hue of each bar representing the organizational structure (i.e., darkest color is the theme and lightest is the specific outcome). Indentation also represents the structure, with furthest indented being the specific outcomes.

Thematic saturation occurred through 16 articles, with 33 contributing no novel outcomes. Of the selected articles, 59% identified at least one sustainability outcome in all three themes of environmental, socio-economic, and health outcomes, 29% identified two, and the remaining 12% identified only one. No article identified all 18 major categories; the articles ranged from 2 to 15 categories, with an average of 6.7 categories per document. Similarly, of a total possible 41 subcategories, the number of identifications ranged from 24 outcomes to one outcome and averaged 7.6.

Finally, we categorized each article as published in a natural science, social science, health, or interdisciplinary journal. While the discipline of the journal is not a perfect match for the disciplinary background of the authors or methods, this proxy was used because, ostensibly, the content of the articles needed to fit the purpose and scope of the journal, and journals contribute to the body of literature of the different fields. For both the environmental and socio-economic outcomes theme, the corresponding discipline (natural science and social science) had the highest percentage of identification. While social science did identify environmental outcomes less often than the other disciplines (60%), only 43% of the natural science journal articles identified an outcome in the socio-economic theme (see Figure 2-3).

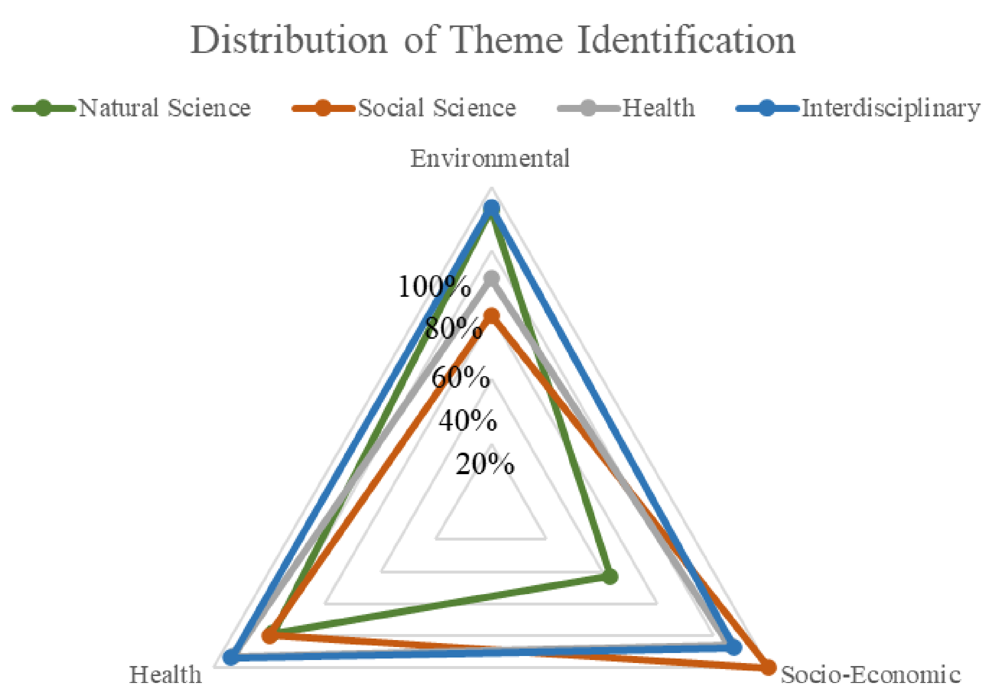

Figure 2-3: Percent of papers in each discipline category identifying at least one outcome within the three themes.

2.5 Discussion

2.5.1 High-Level Trends

2.5.1.1 No single article identified all categories, much less all 93 sustainability outcomes

These results in part justify this systematic review's goal of compiling disconnected information in food systems literature because no single article identified all categories or subcategories of outcomes. The systematic review and coding process also enabled the qualitative creation of a system map based on the connections drawn by the articles included in the systematic review (see Figure 2-4).

2.5.1.2 Lack of disciplinary overlap between natural sciences and social sciences

By organizing the articles into disciplines, we were able to analyze trends within and between different disciplines. While the goal of the search terms was to return articles that used systems lenses and discussed the food system interdisciplinary, the articles from social science journals included in this review discussed environmental outcomes to a higher degree than the natural science counterparts discussed the socio-economic outcomes (see Figure 2-3). The results of the distribution of theme identification by journal discipline also show the success of interdisciplinary journals at identifying outcomes across the sustainability spectrum. This difference in overlap between disciplines is prevalent throughout food systems literature, partially by nature of the disciplinary focuses and the dominant narratives that shaped early food systems work.

However, almost 60% of the articles included a sustainability outcome within all three themes, and almost every article published in an interdisciplinary journal included outcomes across the themes. This result speaks to the success and strength of current interdisciplinary work in the food systems space. While a common knowledge base is still developing for the field, research can and is connecting diverse outcomes using innovative methodologies and partnerships to understand complex socio-environmental systems.

2.5.1.3 High and Low Instances of Coding

High or low instances of coding represent relative prominence of outcomes within the surveyed work. The sample of articles does not encompass the entire field of food systems literature or work on these outcomes outside of the food systems space, so does not imply that these concepts are understudied. For example, there is an entire body of work on animal welfare and ethics, but the outcome is comparatively less prevalent than issues such as environmental pollution or diet-related health effects. However, the implication of lower or higher coding instances can speak to the pervasiveness or the relative importance placed on these outcomes in food systems literature.

2.5.2 System Map

The relationships among outcomes were qualitatively assessed, based on the connections described by the articles included in the systematic review. Causal loop diagramming (CLD) from qualitative data such as interview transcripts or text documents is one way of presenting results (Yearworth & White, 2013). The consolidation of diverse and complex information into a system map necessitates the balancing of fine details and readability/usability. The outcomes included in this map are the categories and subcategories, when appropriate, developed through this review. We organized the diagram specifically to be approachable, comprehensive, and to be useful for continuing conversations about food system dynamics (see Figure 2-4). As this is not a review of system dynamics, the connections were not quantitatively assessed and important external relationships or trade-offs associated with the food system are outside the scope of this paper.

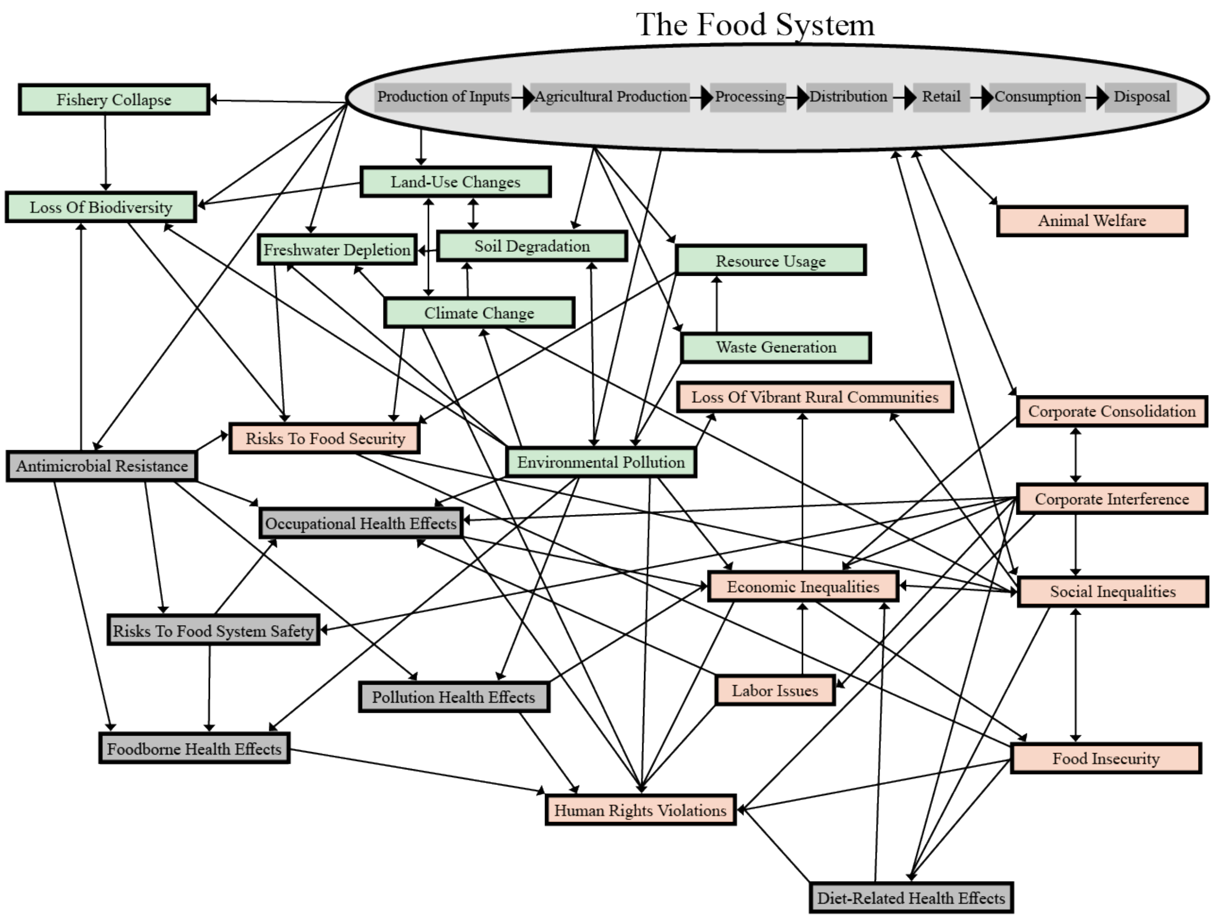

Figure 2-4: Sustainability outcomes map of the US food system. Connection based on reviewed literature, with arrows representing the direction of outcome. The colors represent the organizational structure; green is environmental outcomes, grey is health outcomes.

2.5.3 Limitations

A key limitation of this review is the selection of hand-coding as the data collection process. During the coding process we inferred categories based on qualitative assumptions of similar meanings or connotations among concepts, which introduces limitations such as biases from personal lenses and reduced processing capabilities but enables the collection of more rich and complete data (Weber, 1990). However, these risks were addressed by generating the outcomes and organizational structure from the literature. The hand-coding process is also very time intensive, so several decisions such as limiting the review to peer-reviewed articles and a limited list of databases were made to focus on articles that would efficiently answer the research question. Sources outside of published, peer-reviewed articles likely use different terminology to discuss outcomes or contain more specialized outcomes that are relevant to specific fields, places, or subsystems. Finally, papers that would fit the inclusion criteria likely were published after the review was conducted. These limitations are managed through achieving data saturation, as more sustainability outcomes are unlikely to be identified through including more sources such as grey literature and studies from 2020/21. It is important to note that this review does not encompass the possibility of new outcomes that are connected to COVID-19.

A final limitation is the high-level view on the US food system. Purposely taking a national lens and discussing a topic at a high level of abstraction is ill-suited to encompass all geographic and temporal heterogeneities in the food system. As such, the inventory of sustainability outcomes and connections drawn between them does not reflect all food systems within the US but can be beneficial as a starting point or framework for further work to contextualize a smaller food system with specific actors, decision-makers, and system elements and behaviors. The corollary limitation of focusing on the US is that the review did not include outcomes associated with the globalized food system. Some examples would be deforestation in other countries because of demand in the US or increased water stress in the US due to exported goods, but this was outside the scope of the systematic review and should be included in future related work.

2.6 Conclusions

This review identified 93 sustainability outcomes that represent the diversity of outcomes to the environment, the workers, communities, and consumers involved in the food system.

Sustainability outcomes influence each other and are deeply connected to the physical food system and social, environmental, and economic systems. As evidenced by the relative frequencies of coding in this review, some outcomes are more prevalent than others in the literature, but that does not imply that these are less significant. The goal of our review was to inventory the sustainability outcomes relevant at the national scale. While more depth or details could be added based on smaller scale food systems (for example, specific chemical pollutants, pathogens, or health outcomes relevant to a system or locality), each would most likely fall under one of the established outcomes or categories.

Interdisciplinary research has become more prominent in the last few decades through academic institutionalization of interdisciplinarity and more focus on and funding for inter-/transdisciplinary food systems work, but disciplines can remain siloed and information is still disparate (Hinrichs, 2012). This is demonstrated by the differences in outcome identification density across themes, as 12% of system-level articles only identified outcomes within one theme and no article identified all 18 categories. This trend is certainly not unique to food systems work; much research has disciplinary foci. Food systems literature is also a relatively new, developing field, and through this review we aim to contribute to building a common understanding and interdisciplinarity through the compilation and organization of sustainability outcomes and the discussion of the prevalence of different outcomes in the surveyed literature.

There are several ways in which this review could be used in future research or food systems work. Not all future food systems studies need to consider all the outcomes inventoried by this review, as many will be irrelevant or outside the scope of many research projects or specific research questions. However, the holistic inventory can still be useful as a basis for the purposeful selection of what is or is not relevant to a project. The full list of outcomes can serve as an extensive list of which outcomes or categories could be considered which may be out of the traditional disciplinary scope. A common example would be an agricultural evaluation considering not only the environmental outcome of a pollutant but also the effects on community health. Consulting the full inventory of outcomes may provide additional criteria to assess that would be potentially less intuitive or prevalent.

The inventoried sustainability outcomes can also be used to contextualize work within smaller scoped food systems, as it can provide a broad variety of outcomes upon which to have conversations about, for example, the outcomes of policies or management choices. Other possible uses include as the basis for an assessment tool to evaluate the current state of outcomes and track change over time or identify areas for improvement, as a benchmark of which outcomes have been identified as of 2019 (potentially relevant to studying the food system during or after COVID-19), or as a set of possible evaluation criteria for building a decision support tool based on stakeholder concerns.

Building a holistic understanding of the food systems field is an important first step to more effective and efficient work, through directly incorporating inter-/multidisciplinary knowledge and skills, and acknowledging and addressing the connections of disciplinary topics to other sustainability issues. One benefit of interdisciplinary work would be the ability to coordinate efforts to address multiple sustainability issues concurrently, which can result in efficiencies through goal alignment, selecting a portfolio of interventions, the creation of diverse alliances, and the ability to implement changes at multiple levels (Barnhill et al., 2018; Ruben, Verhagen, & Plaisier, 2019). The inventory generated by this review can be used as a starting point for continued work in food systems and to contextualize changes. The complexity, interdisciplinarity, and scope of the food system ties directly to the extensive sustainability outcomes, which makes sustainable food systems a significant opportunity to impact the well-being of the environment and people in the United States.

2.7 Appendices

2.7.1 Appendix A: Methodology Details

Systematic reviews originated largely in health care as a methodology to critically review literature, conduct meta-analyses, and reach clinical conclusions, but have been applied to other fields (Morton, Berg, Levit, & Eden, 2011). The methodology behind systematic reviews was designed to creating an explicit process for informed choices about the research design, which reduces some selection biases (e.g., unrepresentative or biased selection of articles to be reviewed) that can be present in narrative reviews (Uman, 2011; Collier & Mahoney, 1996). The systematic review steps we took were: 1) formulate a review question, 2) search for existing systematic reviews, 3) write a protocol, 4) devise a search strategy, and 5) execute the search (Tsafnat et al., 2014; Uman, 2011).

Qualitative hand-coding is one common way to examine textual data (Berelson, 1952; Hsieh & Shannon, 2005). Codes can be a word or short phrases that captures the meaning of that segment of text (Nelson et al., 2021; Saldaña, 2021). Hand-coding, as opposed to computer-aided content analysis, comes with trade-offs. Manually reviewing and iteratively coding texts is very time intensive, which can limit the number of texts that can be analyzed (Grimmer & Stewart, 2013; Nelson et al., 2021). However, hand-coding results in more inclusive coding that can capture meaning that can be missed by computer programs. Computer programs can quickly process many texts for common words but, without more complex processes like machine learning, are ill-equipped to manage phrases, indirect references, or other ambiguities (Nelson et al., 2021; Weber, 1990). Hand-coding allows meaning to be analyzed beyond specific words to identify concepts that are communicated through sentences, paragraphs, or with different phrasing (Weber, 1990). This advantage of hand-coding is necessary for the interdisciplinary scope of this review and outweighs the trade-off of additional time.

We developed the search terms to gather papers which focus on the food system in the United States and either discuss or provide some assessment of sustainability outcomes, if not directly using the term sustainability. The final search terms used were food system* AND (assessment OR sustainability*) AND United States*. Asterisks were used at the end of the terms, allowing multiple forms of the word to be present in the search results. An OR qualifier was used to account for some temporal variation or disciplinary conventions, as "sustainability" is not a pervasive term across time or disciplines. The use of "food system" was used to focus the search on papers in the food systems field or that discuss sustainability outcomes at a system-level. The system level, for the purpose of this review, is broadly categorized as the inclusion of multiple system elements and their interactions that are relevant to the US food system. As hundreds of thousands of papers address, to some degree, the sustainability of the food system through work at smaller scopes and/or with higher resolution, our primary rational for choosing system-level sources was to enable a broad, holistic analysis within the logistical bounds of qualitative hand-coding.

The inclusion criteria were developed based on best practices in other peer-reviewed systematic reviews and the scope of the specific research question (Allum, Sturgis, Tabourazi, & Brunton-Smith, 2008; Gruen et al., 2008; Guo & Gifford, 2002; Meijer, Röhl, Bloomfield, & Grittner, 2012; Osbaldiston & Schott, 2012). To be included in the review, content must be peer-reviewed, be written in English, and be published in the last 30 years (1989-2019). The final inclusion criterion limits possible results to focus on more recent articles and thus on the most current and relevant outcomes of the food system (Osbaldiston & Schott, 2012). The articles must encompass the US food system, either by focusing specifically on the US, North America, or cover the global food system. Studies focusing on a single commodity or localized food system were excluded from the analysis.

Several of our choices, such as limiting the sources to peer reviewed articles and excluding very narrow scopes, were shaped by the time intensity of hand-coding. However, some risks are allayed by necessitating data saturation. Data saturation, in this case inductive thematic saturation, is when there is consistent evidence of the same codes being used across documents, so that additional data collection (review of more articles) would likely not result in the identification of new (Guest, Bunce, & Johnson, 2006; Saunders et al., 2018). We calculated saturation by determining which of the reviewed articles contained no new or novel outcomes (i.e., can be coded using existing outcomes), as thematic saturation necessitates finding consistent evidence of the same codes being used across documents (Urquhart, 2012). Achieving thematic saturation means the collected outcomes can be considered a comprehensive inventory.

Database selection was based on coverage of the core disciplines and bodies of knowledge associated with the food system, including natural sciences, social sciences, health, and engineering. Seven databases were chosen based on previous systematic reviews related to food systems: Web of Science, Embase, PsycInfo, ABI/Inform, EconLit, Proquest Materials Science and Engineering, and Sociological Abstracts. While many other databases exist that also contain food systems papers, these seven covered the core disciplines and thus would likely return enough articles to achieve data saturation. If data saturation were not reached within the initially collected articles, we would search additional databases.

2.7.2 Appendix B: Explanation of Outcomes

The following discussion of the inventoried sustainability outcomes is organized into the three main themes: environmental, socio-economic, and human health outcomes. Each section details each outcome and visualizes the categories and subcategories to provide an overview and explanation of each identified outcome and provide connections among outcomes and the food system.

2.7.2.1 Environmental Outcomes:

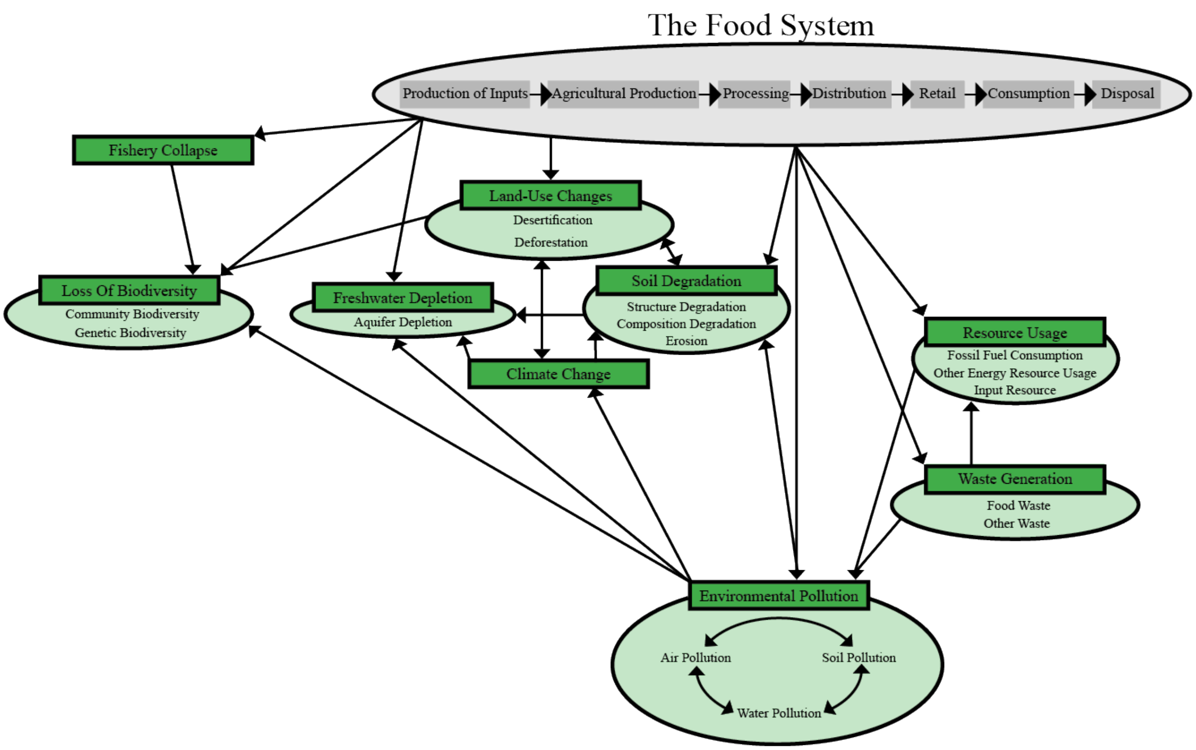

Figure B2-5: Environmental outcomes map of the US food system, outcomes derived from literature review.

The theme of environmental outcomes is split into nine categories: environmental pollution, soil degradation, loss of biodiversity, freshwater depletion, land-use changes, climate change, fishery collapse, waste generation, and resource usage (see Figure 2-5). **Environmental**

pollution was the most often identified category, with 40 out of 49 articles mentioning a concept within that category. The category is split into the three subcategories of **air, water, and soil pollution**. Beginning with air pollution, the food system is a major contributor to **greenhouse gas (GHG) emissions** in the US and is a significant component of the global carbon cycle. Greenhouse gas emissions occur through many processes such as methane emissions from ruminant animals and decomposing organic materials, fossil fuels usage throughout the system, and the burning of crop residue (Heller & Keoleian, 2003; Hickey & Ozbay, 2014; Udeigwe et al., 2015; Wallinga, 2009). The burning of crop residue is also linked to **particulate matter (PM) air pollution**, which can also result from conventional tilling practices, applying biosolids and agricultural chemicals to fields, and feedlot emissions (Rossi & Garner, 2014; Udeigwe et al., 2015; Wallinga, 2009). The final specific outcome within air pollution, **noxious gases**, can also be emitted from food system processes such as ammonia from livestock rearing (Rossi & Garner, 2014; Udeigwe et al., 2015).

Soil pollution, water pollution, and to a lesser extent air pollution are tightly linked due to biogeochemical cycles. As such, the three pollution mediums are circuitously linked in Figure 6. Pollution in one medium often leads to pollution in another, especially in agricultural systems where irrigation or rain carries soil pollutants to water bodies. Pesticides, fertilizers, and biosolids applied to soils, common practices in conventional agriculture, run off through rain or irrigation and pollute surface and groundwater (Udeigwe et al., 2015; Wallinga, 2009). Other pollutants can be present in soils from the use of agricultural **chemicals** or polluted irrigation water (Johnston, Fanzo, & Cogill, 2014; Udeigwe et al., 2015). Another source of contamination is **pathogens** that are spread through the application of biosolids or animal manure to agricultural fields, from direct runoff of leakage from livestock operations or mismanaged manure, or through the irrigation of fields by contaminated water (Chapman & Gunter, 2018; Udeigwe et al., 2015). Water and soil pollutants are tightly linked, as **nutrient** runoff from soils can lead to eutrophication events that damages the health of local flora and fauna (Wallinga, 2009). Water can also become polluted by **particulate matter**, particularly through sediment deposition from erosion (Rossi & Garner, 2014).

The second category is **soil degradation**, that, while linked to soil pollution, focuses on the loss of healthy soil **structure** and **composition**, and the loss of agricultural soils through **erosion**. Soil health is determined by complex interactions between soil biodiversity and soil structures and functions. Biodiversity within soils, for example earthworms, ants, and microbial diversity, have an impact on net primary productivity, which has huge implications for agriculture (Lal, 2007). Certain cropping or grazing practices accelerate rates of erosion, loss of soil organic matter, and other crucial nutrients (Rossi & Garner, 2014; Wallinga, 2009). Soil degradation is a significant problem because soil quality affects the water passing through or over it, and the capacity of soils to retain water, which has implications for water pollution, yield, and resiliency to water scarcity (Lal, 2007).

The **loss of biodiversity** category is split into two subcategories: **genetic biodiversity** and **community biodiversity**. Environmental pollution is a significant driver of biodiversity loss, as it has the potential to damage the local ecosystem through direct events like hypoxia or toxic algae blooms, or through weakening the defenses of organisms and making them more vulnerable to stressors or infection (Wallinga, 2009). Pesticides, pollution from waste generated by the food system, and exposure to antimicrobial resistant bacteria affect community biodiversity (Hickey & Ozbay, 2014; Mohareb, Heller, & Guthrie, 2018; Wallinga, 2009). Several factors influence genetic biodiversity. Firstly, as community biodiversity degrades, the genetic pool shrinks. Secondly, the genetic diversity decreases through selective breeding and genetically modified organisms (GMOs), which are increasingly prevalent. Low genetic diversity increases risk for catastrophic losses from diseases or pests, as there are little to no variation in defensive mechanisms or immunities. Furthermore, the loss of genetic biodiversity in agricultural species, and the ecosystem at large, lowers the adaptive capacities of organisms and their abilities to handle shocks like climate change (Lal, 2007; Shannon, Kim, McKenzie, & Lawrence, 2015). The importance of resilience is reflected in another category, **fishery collapse**. Overfishing can lead to the collapse of many aquatic species and a limited ability to survive additional shocks (Johnston et al., 2014).

Several interconnected categories include **freshwater depletion, land-use changes**, and **climate change**. Climate change and the food system are highly linked. The food system accelerates climate change by emitting GHGs and is vulnerable to the predicted impacts of global climate disruption. As temperatures rise and weather patterns change, it is predicted there will be a loss of soil fertility and disruptions to hydrological cycles, reducing freshwater availability and increasing the need for irrigation (Lal, 2007; Wallinga, 2009). Food production is currently a water-intensive industry, and freshwater depletion through water usage, especially for irrigation, and water pollution, is a serious concern (Lal, 2007). In particular, **aquifers** are a slowly replenishing source of freshwater and withdrawals for irrigation are, in some locations, higher than regeneration rates (Heller & Keoleian, 2003; Udeigwe et al., 2015; Wallinga, 2009). Loss of soil fertility due to the effects of climate change and agricultural processes lower both the ability to produce crops as well as soils' resistance to **desertification** (Lal, 2007). Desertification is just one pressure for land-use change related to agriculture. Urbanization removes potential farmland and reduces viable crop area, while **deforestation** to clear for agricultural land affects global carbon sequestration (Hickey & Ozbay, 2014; Lal, 2007). In addition, land-use change can result in the loss of biodiversity, disruption of natural ecosystems, and overall degradation of the environment (Thyberg & Tonjes, 2016). Land is a stock of carbon that fluctuates based on land-use and treatment, so the usage of land and agricultural practices can be a contributor or detractor to climate change.

The next category, **waste generation**, largely focuses on **food waste and/or loss**. Food waste can occur at any stage of the food system, but emphasis is often placed on post-consumer edible waste as it can be minimized through behavior changes (Conrad et al., 2018). The environmental outcomes are twofold. Firstly, the disposal of food waste through the municipal waste stream uses resources and landfill space, and the decomposition generates methane (Mohareb et al., 2018; Thyberg & Tonjes, 2016). Secondly, the resources, such as water, soil, fossil fuels, and agricultural chemicals that were used to produce the food is wasted (Hickey & Ozbay, 2014; Thyberg & Tonjes, 2016). This reduces the efficiency of the food system and increases the environmental burden. **Other wastes** generated by the food system include packaging wastes from transportation and shipping or food packaging like plastic wraps, corrugated boxes, etc. (Heller & Keoleian, 2003; Mohareb et al., 2018). Waste, from litter to microplastics or organic pollutants in wastewater, have a diversity of impacts on ecosystem health.

The final category in the environmental outcome theme is **resource usage**, specifically non-renewable resources. As discussed previously, the food system is largely dependent on **fossil fuels** to produce agricultural inputs, irrigate fields, operate machinery, house animals, and transport, process, retail, store, and prepare food (Johnston et al., 2014; Shannon et al., 2015). **Other energy resources** like electricity is used for several of those processes, including irrigation, food processing machinery, refrigeration, and at-home appliances, and depending on electricity grid emissions factor, are associated with GHG emissions (Heller & Keoleian, 2003; Mohareb et al., 2018). Other non-renewable **input resources** include phosphate rocks mined for fertilizers, chemicals such as pesticides, and pharmaceuticals like antibiotics (Lal, 2007; Shannon et al., 2015; Wallinga, 2009).

2.7.2.2 Socio-Economic Outcomes:

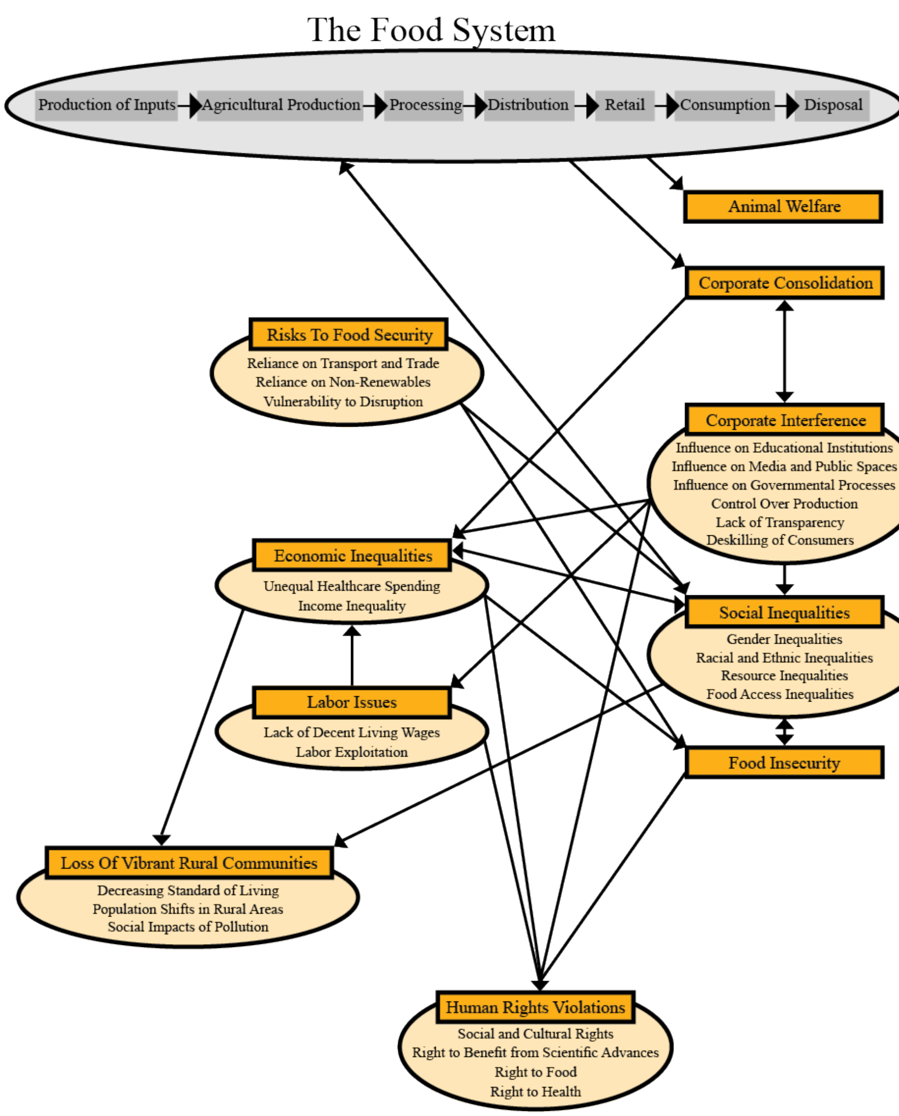

Figure B2-6: Socio-economic outcomes map of the US food system, outcomes derived from literature review.

The theme of socio-economic outcomes is split into three categories: **social outcomes**, **economic outcomes**, and **risks to food system security** (Figure 2-6). Many social, economic, and health outcomes are circuitously linked, as systemic discrimination and disenfranchisement drives economic inequalities and disproportionate health outcomes, which in turn serve as barriers to equity and justice. There are also many trade-offs associated with social and economic systems, as benefits for one group of people, for example employees in a sector, residents of an area, or social identity group, may be at the detriment of another. While some of these nuances will be discussed below, there are many aspects of society, economics, and politics in the US that are relevant to the food system that are not encompassed by this review. For example, the social, economic, and health outcomes for workers will be discussed, but further details on the drivers of these conditions, such as immigration and labor laws, will not be explored in depth. As previously stated, a primary goal is to inventory the outcomes of the food system, and a comprehensive analysis of system drivers is beyond the scope of this review.

The social outcomes category contains six subcategories: social inequalities, food insecurity, human rights violations, loss of vibrant rural communities, corporate interference, and animal welfare. **Social inequalities** are a broad subcategory that spans **gender, racial and ethnic, resource, and food access inequalities**. The food system is both subject to and upholds structural discrimination. Discriminatory pressures and historical disenfranchisement have influenced food system structure, but the behavior of the food system maintains inequalities through the distribution of or access to resources and opportunities. Agricultural practices in the US have a deep history of discrimination and colonization through the privatization and commodification of land by white and wealthy individuals (Horst & Marion, 2019). The United

States exists because of the dispossession of land from indigenous peoples through physical violence and manipulation. The development and execution of agriculture and the food industry in the United States has depended on the exploitation of marginalized groups throughout history, including the enslavement of millions of Africans and discriminatory treatment of immigrants (Horst & Marion, 2019). These practices, for example, policies in the late 19^{th} and early 20^{th} century banning Asian Americans from owning land, inheritance laws that made it difficult for women to possess land, or complex immigration policies, shaped who is allowed or able to own land (Horst & Marion, 2019). Women historically shoulder the brunt of food procurement and preparation responsibilities in the home, which is economically undervalued labor, knowledge, and skills (Jaffe & Gertler, 2006). Gender, racial, and ethnic inequalities exist throughout the food system and are connected to other social, economic, and health outcomes.

The final two subcategories of social inequalities are **resource** and **food access inequalities**. Resource inequalities include aspects like education, healthcare, and opportunities (Cachelin, Ivkovich, Jensen, & Neild, 2019). Unequal distribution of resources can impact people's health, wellbeing, and ability to pursue their desires. For example, women and people of color are less likely to be recipients of lending from the USDA, an opportunity to gain capital necessary to start an agricultural operation (Horst & Marion, 2019). Food access, both amount and types of food, is not equitable. City planning, private sector investment, and federal subsidies led to supermarkets being largely located in suburbs, lowering the accessibility of fresh produce in city centers and rural areas (Anderson, 2008; Elmes, 2018). The food available in these underserved areas are more often processed, convenience food that are high calorie and nutrient-poor, the consumption of which can lead to health outcomes (Anderson, 2008; Cachelin et al., 2019).

Food insecurity affects millions of households in the United States every year, and disproportionately affects women, people of color, and recent immigrants (Anderson, 2008; Cachelin et al., 2019). Food insecurity can be influenced by food access inequalities, and is influenced by income, food price, cultural suitability of food, and food preparation knowledge and skills. The outcomes of food insecurity are multifold, as hunger impacts individuals' ability to focus (particularly damaging for food insecure students), cognition, decision-making, and risk-taking behavior (Elmes, 2018). Government nutritional assistance programs like SNAP or WIC, while important stop gaps, do not address the root of the problem, like economic inequalities, and often do not provide recipients with necessary funds to purchase more expensive, healthy foods (Anderson, 2008). There is a relationship between poverty, food insecurity, and obesity as filling, processed foods are often both cheap and unhealthy (Elmes, 2018). Some potential benefits of reducing food waste would be that the diverted waste could be used to reduce food insecurity, or that avoided food waste increases food availability (Hickey & Ozbay, 2014). However, global agriculture produces enough calories to sustain the population, which implies that food insecurity is more likely a distributional and economic issue than a lack of production quantity (McInnes & Mount, 2017).

The next category is **human rights violations**, which does not have a universal definition; there is disagreement about what constitutes a human right (Anderson, 2008). Economic, social, and cultural rights like the **right to food, health, or a livable income** are violated by the food system through outcomes like food insecurity and access inequalities, environmental pollution, unsafe workplaces, and lack of decent living wages. **Social and cultural rights** include aspects like intergenerational justice, the right to participate in cultural life, and right to democratic participation in decisions about the food system (Anderson, 2008).

Climate change, which the food system accelerates, fundamentally impinges upon intergenerational justice. The loss of traditional foodways, the cultural practices surrounding food, reduces peoples' ability to practice and enjoy their culture (Anderson & Cook, 1999; Cachelin et al., 2019). Food is not simply a nutritional input necessary for physical functioning, but an aspect of identity, family, and community. The concept of food sovereignty includes the right of people to have culturally appropriate foods, but also their right to democratically shape the food system to suit social and environmental values, which is difficult due to lack of information about the food system and corporate interference with the policy process (Anderson & Cook, 1999; Cachelin et al., 2019). The final outcome under the subcategory of human rights violations is the **right to benefit from scientific advances**. Much of the public funding for food systems research and technological advances focuses on cropping methods like genetically engineered monocrops and mechanization, which economically undermines mid-/small-scale and/or sustainable farmers (Anderson, 2008).

The following category, **loss of vibrant rural communities**, contains the subcategories of **decreased standard of living, population shifts**, and **negative social impacts of pollution**, which are driven in part by the food system. Trends like industrialization and urbanization shifted populations, especially young people, from rural to urban areas (Anderson, 2015). While population shifts are not by definition negative, and advances in mechanization has freed up individuals to pursue other jobs, both trends have directly and indirectly impacted rural areas. Rural areas have fewer job opportunities, and the industries that moved into rural areas tend to be less skilled work and lower wages, like call centers, prisons, and factories (Anderson, 2008). The lower economic value and dispersed population in rural areas led to lower quality public services like education and public transportation, and access to health care and retail services (Anderson, 2008; Bardenhagen, Pinard, Pirog, & Yaroch, 2017; Hallam et al., 1993). Lack of well-paying jobs, and more localized, environmental pollution, have made rural areas undesirable to many (Anderson, 2008; Hallam et al., 1993; Rossi & Garner, 2014). The "hollowing out" of rural areas impacts the social well-being of rural occupants and their ability or willingness to participate in community institutions (Anderson, 2008, 2015; Hallam et al., 1993; Rossi & Garner, 2014). Although the shift to urban centers has slowed considerably, rural populations are aging, have declining birthrates, and face inequalities in income, health outcomes, and resource and food distribution (Anderson, 2015).

Animal welfare is also a significant concern in the food system. There are many dimensions to animal welfare, including living conditions, treatment, and genetic selection (Hoetzel, 2014). While there are arguments that killing living creatures can never be ethical, it is undeniable that industrial livestock production is inhumane. Selective breeding is used for traits like higher body weight or quicker egg production, but these changes can result in discomfort and loss of quality of life as, for example, broiler chicken have difficulty moving around with enlarged breast tissue (Hoetzel, 2014; Rossi & Garner, 2014). Efficiency-focused industrialization led to compact and mechanized rearing systems that rely on antimicrobials and growth hormones to maximize net yield and manage diseases in over-crowed and immunologically stressful conditions (Hoetzel, 2014; Rossi & Garner, 2014). These conditions restrict movement and generate mental distress for animals. Animals undergo other inhumane treatments during rearing transportation, and processing in slaughterhouses, such as cutting off tails, beaks, and horns or scaling, skinning, or dismemberment, often without anesthesia or while animals are conscious (Hoetzel, 2014; Rossi & Garner, 2014).

The final subcategory is **corporate interference**. The food system is a highly industrialized, corporatized, and capitalized industry. Food is a commodity, a product with which to extract value through private ownership of land and the means of production (Elmes, 2018). The accumulation and abuse of power by firms in the food system are critiqued for several reasons, including the privatization of natural resources, unequal distribution of food, and the **manipulation of political, educational, and social systems** for financial gain. Corporations can privately fund research that provides them with advantages, which can in turn further wealth gaps or monopolies of large firms and violates the right to benefit fairly from scientific advances (Anderson, 2008; Elmes, 2018). Firms can also capture the policy process through political donations and pressures from lobbyists to, for example, roll back environmental legislation, weaken anti-trust laws, or influence the allocation of public research dollars (Elmes, 2018; Wallinga, 2009).

Consumers can be influenced through advertising, branding, labeling, and news in media and public spaces. The agro-food industry spends billions of dollars to market their products, which can be misleading or manipulative (Anderson, 2008; Elmes, 2018; Jaffe & Gertler, 2006; Shannon et al., 2015). Branding and labeling may also be used as a purposeful **lack of transparency**, which can make it difficult for consumers to understand the health or sustainability impacts of their food choices (Elmes, 2018). There is also a lack of transparency around agricultural practices, value chains, or brand ownership which removes the information and understanding of the food system necessary for consumers to be able to make informed decisions in-line with their values (Jaffe & Gertler, 2006). The disconnect of consumers from the production of food, and thus their awareness of the process and understanding of environmental and social externalities, is a form of **deskilling consumers** (Anderson, 2008; Jaffe & Gertler, 2006). The shift towards convenience foods, both through changing lifestyles and pressures from food firms, also deskilled consumers as they lose knowledge and skills about how to prepare food, nutrition and the health of foods, and freshness and spoilage (Elmes, 2018; Heller & Keoleian, 2003; Jaffe & Gertler, 2006). The deskilling of consumers affects health, participation in cultural traditions, and the ability of consumers to recognize problems and advocate for solutions within the food system (Jaffe & Gertler, 2006).

The category **risks to food security** is in the socio-economic theme because a loss of food security would result in increased food insecurity or food access inequalities. The three specific outcomes discussed in the reviewed literature are the food system's **vulnerability to disruption, reliance on non-renewables**, and **reliance on transportation and trade**. The food system is a highly complicated set of interconnected systems that largely cannot operate alone. As such, the food system is vulnerable to disruption at many points and scales, such as natural disasters, climate change, freshwater depletion, emergent pests or diseases, or bioterrorism (Gilmore, 2004). The intensive use of non-renewable resources, such as fossil fuels and antibiotics, endangers the longevity of the food system as these resources will eventually run out (Blair & Sobal, 2006; Conrad et al., 2018; Wallinga, 2009). Finally, the US food system is highly dependent on national and international transportation and trade to provide adequate nutrition and diet diversity to its citizens (Gilmore, 2004; Koc & Dahlberg, 1999). In the event of halted or disturbed transportation and trade, much of the United States would not be able to provide adequate food to its citizens.

While the ultimate negative outcomes of economic issues are most often the resulting social or health issues, such as damages to mental, social, or physical well-being, it can be useful to discuss economic outcomes as individual issues and as precursors to further problems. In addition, many consider fair employment to be a human right. The subcategories in the economic outcome category are corporate consolidation, economic inequalities, and labor issues.

Corporate consolidation is rampant throughout the food system, like agrochemical or biotechnology companies who produce agricultural inputs, agrobusinesses who produce food, food processors, transportation and multinational trade firms, grocery retailers, and restaurants. In 2019, 3% of farms generated 46% of the value of production (USDA, 2019a). Both vertical and horizontal integration exist in the food system, which refers to integration either along the food system (i.e., a firm that produces, processes, and sells a product) or within a system stage (i.e., a firm that owns a large market share of a particular industry) respectively. The consolidation process is in a positive feedback loop with corporate interference, as the power gained through consolidation can be leveraged to influence the mechanisms that would decrease power, such as anti-trust legislation. The most obvious examples of consolidation are large food brands or retailers, but less consumer-facing aspects of the food system, such as wholesale and food distribution firms are also consolidated (Elmes, 2018). Livestock slaughtering and packing is also a consolidated industry, with dramatic trends towards larger factories and fewer firms (MacDonald, Ollinger, Nelson, & Handy, 2000).

Corporate consolidation is not inherently negative, and this outcome refers specifically to the negative sustainability outcomes enabled by concentration that are pervasive in the US food system. In isolation, consolidation presents a risk that if needs and desires of a population change, entities with highly consolidated power can resist change, dictate conditions, and act out of line with social and environmental good. Corporate consolidation concentrates power which enables impactful decision-making, but runs the risk of being abused (Anderson, 2008, 2015; Elmes, 2018). There is reduced competition, either through mergers, takeovers, or difficulties entering the market, which entrenches the control of consolidated firms and removes the ability of consumers to express values through purchasing decisions (Anderson, 2015; Elmes, 2018; Jaffe & Gertler, 2006). Consolidation also weakens local markets, which impacts local economies and takes wealth out of communities that they are unlikely to recoup (Anderson, 2015; Johnston et al., 2014; Yang & Suh, 2015).

The final two subcategories are **economic inequalities** and **labor issues**. Economic inequalities exist in the food system, including **income inequality** and **unequal healthcare spending**. Income inequality is a significant issue for farmers, food processing workers, and food service workers, as they do not benefit fairly from the wealth generated by the food system (Anderson, 2008; Heller & Keoleian, 2003; Horst & Marion, 2019; Wallinga, 2009). Agriculture and food related industries contributed $1.053 trillion, or 5.4%, to the US gross domestic product in 2017, and 11% of employment, 22 million jobs, in 2019 (USDA, 2017; USDA, 2019b). In addition, rural areas face higher income inequality and unemployment then their metropolitan counterparts (Hallam et al., 1993; Rossi & Garner, 2014). Unequal healthcare spending due to health burdens caused by the food system, mainly environmental pollution and occupational health effects, can be worsened by distributional inequalities of healthcare services, especially in non-metro areas, and low quality or lacking health insurance for food system employees (Blair & Sobal, 2006; Rossi & Garner, 2014; Wallinga, 2009).

Income inequality is a prominent issue due to the lack of living wages provided to food system employees (Anderson, 2008, 2015; Horst & Marion, 2019; Lo & Delwiche, 2015). **Decent living wages** are a cornerstone of fair employment (Anderson, 2008). Beyond lower wages, but contributing to economic inequalities, is **labor exploitation** (Elmes, 2018; Horst & Marion, 2019). This includes practices like unpaid labor, forced labor, wage theft, the inability to form labor unions, child labor, or other forms of exploiting vulnerable populations such as immigrants, and particularly undocumented workers (Anderson, 2008; Heller & Keoleian, 2003; Lo & Delwiche, 2015; Pilgeram, 2011). Suppressing labor unions, a practice that is aided by corporate consolidation and interference, is particularly harmful because it removes the ability of workers to advocate for themselves and improve aspects like wages or workplace health and safety (Anderson, 2008). Thus, while labor issues are linked to economic outcomes, they can also result in outcomes to physical and mental well-being.

2.7.2.3 Human Health Outcomes:

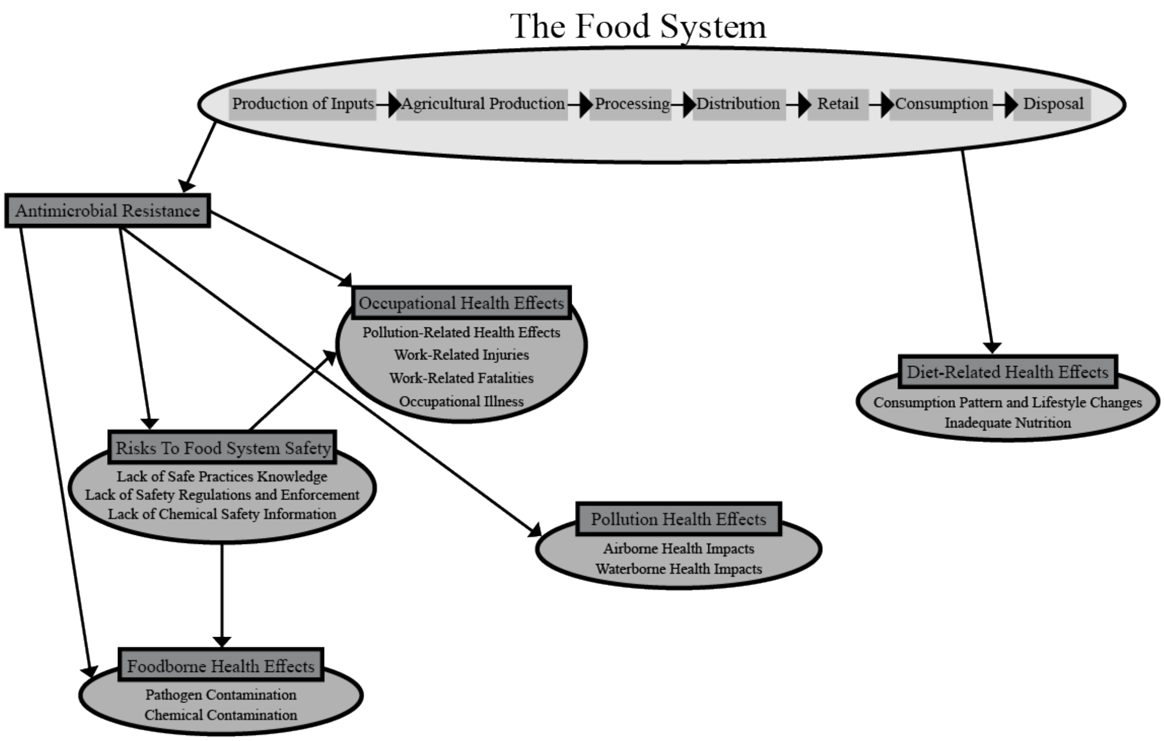

Figure B2-7: Human health outcomes map of the US food system, outcomes derived from literature review.

The theme of human health outcomes covers the categories of health effects from environmental pollution, diet-related health effects, antimicrobial resistance, foodborne health effects, occupational health effects and risks to food system safety (see Figure 2-7). **Environmental pollution** affects communities surrounding food system activities through two main pathways: **air and water**. Air pollution such as particulate matter and noxious gases can contribute to respiratory issues like asthma, while both inhaled or consumed agricultural chemicals, like pesticides, can contribute to health issues such as cancer, neurologic diseases, or act as endocrine disruptors (Blair & Sobal, 2006; Rossi & Garner, 2014; Udeigwe et al., 2015; Wallinga, 2009). Pathogen pollutants in water can spread zoonotic diseases or other pathogens (Hallam et al., 1993; Rossi & Garner, 2014). In some cases, eutrophication events from nutrient pollution can create toxic algae blooms that render drinking water unconsumable.

Diet-related health effects are separated into the two categories of **consumption pattern and lifestyle changes** as well as **inadequate nutrition**. The interplay among consumptions patterns, lifestyle choices, and individual physiology is complex and highly variable. While diet does not impact all people equally, it does have a significant impact on health. **Consumption patterns** in the United States shifted over time to include more processed calorie-dense, nutrient-poor foods, animal products, larger portion sizes, and more meals eaten outside of the home (Hickey & Ozbay, 2014; Rossi & Garner, 2014; Wallinga, 2009). Simultaneously, **lifestyles** have become more sedentary (Kearney, 2010). These factors have a direct link to obesity, which is a significant public health concern in the United States and is a contributor to other diet-related health issues like diabetes, cardiovascular disease, and hypertension (Blair & Sobal, 2006; Finley et al., 2017; Johnston et al., 2014; Neff, Merrigan, & Wallinga, 2015; Nelson, Hamm, Hu, Abrams, & Griffin, 2016b). Dietary choices can influence a range of health concerns from kidney disease to arthritis to cancer (Nelson et al., 2016b; Shannon et al., 2015). **Inadequate nutrition** includes malnutrition through a lack of sufficient food or micronutrient deficiencies (Johnston et al., 2014; Merrigan et al., 2015; Rose, Heller, & Roberto, 2019; Wilkins, Lapp, Tagtow, & Roberts, 2010).

A common influence on human health is foodborne contaminants like pathogens and chemicals. Pathogens can be present in animal products and transferred to produce through application of animal manures or biosolids, irrigation with contaminated water, contamination of harvesting, transportation, and processing equipment, or cross-contamination with other foods (Chapman & Gunter, 2018; Fraser & Simmons, 2017; Gelting & Baloch, 2013). Common pathogens which lead to foodborne illness are *Salmonella*, norovirus, and *E. coli* (Chapman & Gunter, 2018; Rossi & Garner, 2014; Stuart & Worosz, 2012). It is also possible that foods could be contaminated with harmful chemicals along the food system (Fraser & Simmons, 2017; Maffini, Neltner, & Vogel, 2017).

The next category, antimicrobial resistance, occurs when target organisms develop a resistance to an antimicrobial. This is a multifold concern in the food system. From a public health perspective, antimicrobials, particularly antibiotics, are an important line of defense. The high rate of antibiotic usage on livestock speeds the development of resistance and transmittance to humans, while decreasing the effectiveness of antibiotics in other situations (Wallinga, 2009). This is also an ongoing process for fungicides and pesticides, and while the latter does not as directly impact human health, there are significant implications for agricultural yield.

Similar to previous categories, **occupational health outcomes** occur throughout the food system, and is broken into the subcategories of occupational illness, work-related injuries and fatalities, and occupational pollution-related health effects. **Occupational illnesses** can be the result of exposure to pathogens or zoonotic diseases, and food system workers have a higher risk of exposure than the general public (Neff et al., 2015; Rossi & Garner, 2014). Workers in the livestock rearing, slaughter, and processing supply chain are also at higher risk of being exposed to antimicrobial resistant bacteria (Rossi & Garner, 2014). Agriculture and food manufacturing has a high rate of **work-related injuries and fatalities** from accidents than other industries (Neff et al., 2015; Newman, Leon, & Newman, 2015). Work-related injuries include acute and chronic injuries, such as chronic back pain or musculoskeletal problems from repetitive motions or long hours standing (Newman et al., 2015). **Pollution** in the workplace can also contribute to health outcomes like respiratory issues from irritation to serious conditions like respiratory diseases and asthma (Rossi & Garner, 2014; Shannon et al., 2015). Exposure to pesticides can result in a variety of health effects, including mortality from acute pesticide poisoning (Rossi & Garner, 2014; Wallinga, 2009). Occupational health effects can be worsened through lacking or improperly enforced health and safety practices.

The final category in human health outcomes is **risks to food safety**. Food safety is impacted by a **lack of knowledge on safe practices**, leading to mishandled food and increases in foodborne health outcomes, **lack of chemical safety information**, particularly the risks of multiple interacting chemicals, and a **lack of safety regulations and enforcement** (Chapman & Gunter, 2018; Maffini et al., 2017; Stuart & Worosz, 2012; Taylor & Hoffmann, 2001). Chemicals are notoriously under-studied, as many have not been extensively tested and still used as they are “generally recognized as safe” (GRAS) (Maffini et al., 2017). There are thousands of chemicals added to foods, which poses a challenge for responsible management by the FDA in isolation, much less when considering chronic low-level exposure, exposure for vulnerable populations like children, or multiple chemical interactions (Jaffe & Gertler, 2006; Maffini et al., 2017; Taylor & Hoffmann, 2001). Food safety and the safety of food system employees is further at risk due to lacking safety regulations, limited food and facility inspections, and a minimal response from firms to address safety concerns (Stuart & Worosz, 2012; Taylor & Hoffmann, 2001).

2.7.3 Appendix C: Raw Coding + Additive Coding

Table C2-2 Results of raw coding and additive coding.

Outcome:	Raw:	Additive:
Environmental Outcomes	11	41
Environmental Pollution	16	40
Air Pollution	5	26
Greenhouse Gas Emissions	23	23
Particulate Matter Air Pollution	2	2
Noxious Gases Air Pollution	3	3
Water Pollution	24	29
Water Nutrient Pollution	20	20
Water Pathogen Pollution	4	4
Water Chemical Pollution	9	9
Particulate Matter Water Pollution	8	8
Soil Pollution		7
Soil Chemical Pollution	5	5
Soil Pathogen Pollution	2	2
Soil Degradation	14	21
Soil Structure Degradation	2	2
Soil Composition Degradation	4	4
Erosion	14	14
Loss Of Biodiversity	13	18
Genetic Biodiversity	6	6
Community Biodiversity	5	5
Freshwater Depletion	24	24
Aquifer Depletion	7	7
Land-Use Changes	14	17
Deforestation	5	5
Desertification	2	2
Climate Change	17	17
Fishery Collapse	2	2
Waste Generation		18
Food Waste	15	15
Other Waste Generation	4	4
Resource Usage	9	21
Fossil Fuel Consumption	11	11
Input Resource	3	3
Other Energy Resource Usage	7	7
Socio-Economic Outcomes		37

Social Outcomes	5	31
Social Inequalities	3	14
Gender Inequalities	5	5
Racial And Ethnic Inequalities	3	3
Resource Inequalities	5	5
Food Access Inequalities	10	10
Food Insecurity	15	15
Human Rights Violations	5	10
Social And Cultural Rights	3	8
Right To Food	4	4
Right To Health	2	2
Right To Benefit From Scientific Advances	3	3
Loss Of Vibrant Rural Communities	5	11
Decreasing Standard Of Living	6	8
Population Shifts In Rural Areas	3	3
Social Outcomes Of Pollution	4	4
Corporate Interference	1	16
Influence On Educational Institutions	3	3
Influence On Media And Public Spaces	5	5
Influence On Governmental Processes	7	7
Control Over Production	8	8
Lack Of Transparency	4	4
Deskilling Of Consumers	10	10
Animal Welfare	5	5
Risks To Food Security	13	21
Vulnerability To Disruption	3	3
Reliance On Non-Renewables	9	9
Reliance On Transportation And Trade	2	2
Economic Outcomes		22
Corporate Consolidation	14	14
Economic Inequalities	5	18
Income Inequality	11	11
Unequal Healthcare Spending	4	4
Labor Issues	3	7
Lack Of Decent Living Wages	4	4
Labor Exploitation	6	6
Human Health Outcomes	5	43
Environmental Pollution Health Effects	4	11
Airborne Health Outcomes	7	7
Waterborne Health Outcomes	5	5

Diet-Related Health Effects	27	33
Consumption Pattern And Lifestyle Changes	14	26
Diabetes	11	11
Cardiovascular Disease	12	12
Obesity	17	17
Hypertension	4	4
Inadequate Nutrition	11	11
Antimicrobial Resistance	7	7
Foodborne Health Effects	1	18
Pathogen Contamination Of Food	12	12
Chemical Contamination Of Food	3	3
Occupational Health Effects	7	15
Occupational Illness	6	6
Work-Related Injuries	7	7
Work-Related Fatalities	6	6
Occupational Pollution-Related Health Effects	6	6
Risks To Food System Safety	14	14
Lack Of Safe Practices Knowledge	1	1
Lack Of Safety Regulations And Enforcement	2	2
Lack Of Chemical Safety Information	3	3
TOTAL:	**728**	**1074**

2.7.4 Appendix D: List of Reviewed Articles

Table D2-3 List of reviewed articles with title and citation.

Title:	Citation:
Improving Farm Animal Welfare: Is Evolution or Revolution Needed in Production Systems?	(Hoetzel, 2014)
Understanding Sustainable Diets: A Descriptive Analysis of the Determinants and Processes That Influence Diets and Their Impact on Health, Food Security, and Environmental Sustainability	(Johnston et al., 2014)
Soil Science and the Carbon Civilization	(Lal, 2007)
Roles of Rural Areas in Sustainable Food System Transformations	(Anderson, 2015)
Options for keeping the food system within environmental limits	(Springmann et al., 2018)
Leveraging foodways for health and justice	(Cachelin et al., 2019)
Food Sustainability in the Context of Human Behavior	(Morawicki & Díaz González, 2018)
Implications of leading crop production practices on environmental quality and human health	(Udeigwe et al., 2015)
Victual Vicissitudes: Consumer Deskilling and the (Gendered) Transformation of Food Systems	(Jaffe & Gertler, 2006)
The restructuring of food systems: Trends, research, and policy issues	(Koc & Dahlberg, 1999)
Luxus Consumption: Wasting Food Resources Through Overeating	(Blair & Sobal, 2006)
Racial, ethnic and gender inequities in farmland ownership and farming in the U.S.	(Horst & Marion, 2019)
Risk, anti-reflexivity, and ethical neutralization in industrial food processing	(Stuart & Worosz, 2012)
Industrial Farm Animal Production: A Comprehensive Moral Critique	(Rossi & Garner, 2014)
Relationship between food waste, diet quality, and environmental sustainability	(Conrad et al., 2018)
The Progressive Increase of Food Waste in America and Its Environmental Impact	(Hall, Guo, Dore, & Chow, 2009)
Rights-based food systems and the goals of food systems reform	(Anderson, 2008)
Characterizing Rural Food Access in Remote Areas	(Bardenhagen et al., 2017)
Local Food Systems Food Safety Concerns	(Chapman & Gunter, 2018)
Economic Inequality, Food Insecurity, and the Erosion of Equality of Capabilities in the United States	(Elmes, 2018)
The Evolution of the School Food and Farm to School Movement in the United States: Connecting Childhood Health, Farms, and Communities	(Feenstra & Ohmart, 2012)
Nutritional Sustainability: Aligning Priorities in Nutrition and public health with Agricultural Production	(Finley et al., 2017)
Food Safety Education: Training Farm Workers in the US Fresh Produce Sector	(Fraser & Simmons, 2017)
A systems analysis of irrigation water quality in environmental assessments related to foodborne outbreaks	(Gelting & Baloch, 2013)
US food safety under siege?	(Gilmore, 2004)
Sustainable Food and Agricultural Policies: A U.S. Perspective	(Hallam et al., 1993)
Assessing the sustainability of the US food system: a life cycle perspective	(Heller & Keoleian, 2003)
Food Waste in the United States: A contributing factor toward environmental instability	(Hickey & Ozbay, 2014)
The effects of the industrialization of US livestock agriculture on promoting sustainable production practices	(Hinrichs & Welsh, 2003)

Supporting Equitable Food Systems Through Food Assistance at Farmers' Markets	(Jones & Bhatia, 2011)
Role of Veterinary Medicine in Public Health: Antibiotic Use in Food Animals and Humans and the Effect on Evolution of Antibacterial Resistance	(Lathers, 2001)
The Natural Resource Limits of US Agriculture	(Libby, 1993)
The Good Food Purchasing Policy: A tool to intertwine worker justice with a sustainable food system	(Lo & Delwiche, 2015)
We are what we eat: Regulatory gaps in the United States that put out health at risk	(Maffini et al., 2017)
Designing a sustainable diet	(Merrigan et al., 2015)
Cities' Role in Mitigating United States Food System Greenhouse Gas Emissions	(Mohareb et al., 2018)
A Food Systems Approach to Healthy Food and Agriculture Policy	(Neff et al., 2015)
Alignment of Healthy Dietary Patterns and Environmental Sustainability: A Systematic Review	(Nelson et al., 2016b)
Estimating Occupational Illness, Injury, and Mortality in Food Production in the United States: A Farm-to-Table Analysis	(Newman et al., 2015)
Energy Intensity of Agriculture and Food Systems	(Pelletier et al., 2011)
"The Only Thing That Isn't Sustainable…Is the Farmer": Social Sustainability and the Politics of Class among Pacific Northwest Farmers Engaged in Sustainable Farming	(Pilgeram, 2011)
Position of the Society for Nutrition Education and Behavior: The Importance of Including Environmental Sustainability in Dietary Guidance	(Rose et al., 2019)
Food system policy, public health, and human rights in the United States	(Shannon et al., 2015)
Redesigning Food Safety: Using Risk Analysis to Build a Better Food Safety System	(Taylor & Hoffmann, 2001)
Drivers of food waste and their implications for sustainable policy development	(Thyberg & Tonjes, 2016)
Sustainability of the US dairy industry	(von Keyserlingk et al., 2013)
Today's Food System: How Healthy Is It?	(Wallinga, 2009)
Beyond Eating Right: The Emergence of Civic Dietetics to Foster Health and Sustainability Through Food System Change	(Wilkins et al., 2010)
Changes in environmental impacts of major crops in the US	(Yang & Suh, 2015)

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Chapter 3 Modeling Complex Problems by Harnessing the Collective Intelligence of Local Experts: New Approaches in Fuzzy Cognitive Mapping[2]

3.1 Abstract

Developing system understanding and testing interventions are critical steps to addressing wicked problems. Fuzzy cognitive mapping (FCM) can be a useful participatory modeling tool that enables aggregation of individual perspectives to build system models that represent groups' collective intelligence (CI). However, current FCM aggregation methodologies for creating CI models have rarely been tested and compared. We conducted 51 FCM interviews with local experts in the Flint, MI food system to map their mental models about how different food system sectors influenced desirable outcomes. Using four differing aggregation techniques, based on experts' identity diversity and cognitive diversity, we generated four CI models. The models were compared based on their similarity to real-world complex systems using performance metrics like network structure, micro-motifs, cognitive distance, and scenario outcomes. We found that using cognitive diversity to group individuals was better suited for modeling systems with diverse holders of knowledge.

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3.2 Introduction

Wicked problems are fundamentally difficult to understand and manage. They are marked by uncertainty, complexity, trade-offs, and counterintuitive causal relationships (Head and Alford, 2015; Rittel and Webber, 1973; Turner et al., 2017). The complex socio-environmental systems that produce wicked problems like poverty, climate change, or food insecurity are generally decentralized, with diverse groups of stakeholders and bodies of governance with independent and often conflicting interests that can make top-down solutions ineffective (Weber and Khademian, 2008). Furthermore, wicked problems often have no definitive solution, but rather multiple possible interventions that can range in quality and differ in stakeholder preference (Head and Alford, 2015; Rittel and Webber, 1973). Even reaching the decision-making stage can be trying, as researchers or stakeholders first need to establish an understanding of the issue to identify and evaluate possible actions.

Methods for understanding, much less addressing, wicked problems remain somewhat elusive. A combination of fields is required, including complex systems, decision-sciences, and modeling, in order to deepen system understanding and promote collaboration among actors to achieve collective action (Freeman et al., 2020). Using a case study of food insecurity in Flint, MI, we propose a fuzzy cognitive mapping (FCM) methodology for aggregating the knowledge of experts. Aggregation is the process of combining multiple FCMs into a single model, which we will refer to in this paper as a "metamodel." Generally, the goal of aggregation is to create a more accurate and parsimonious representation of a system. FCMs can be aggregated into a metamodel by grouping participants with either homogenous or heterogenous expertise. Using a bottom-up system approach to understanding wicked problems, FCM allows researchers, community leaders, and policymakers to integrate principles of participatory system modeling with collective intelligence theory (Gray et al., 2020). FCM can be effectively used to aggregate local knowledge, evaluate interventions (leverage points), and engage community members to assist in decision-making that puts possible interventions into practice. Mental models are grounded in constructivist psycho- logical theories which assert that individuals organize knowledge and information into mental systems (Craik, 1952; Gray et al., 2014, 2015; Voinov et al., 2018). These internal abstractions of the real world can be externalized during an FCM modeling session and represented as a network with directed and weighted causal connections between components (Gray et al., 2014, 2015; Stylios and Groumpos, 2004). Systems approaches, like FCM, are used at a variety of scales to develop a holistic understanding of the structure and dynamics of complex systems that is needed to design and implement multi-level management strategies that maximize desired outcomes and minimize undesired outcomes (Barnhill et al., 2018; Ruben et al., 2019). The semi-quantitative nature of FCMs enables "what-if" analysis through scenario testing, which is useful for testing system sensitivity to change, deepening understanding of system dynamics, and evaluating proposed interventions (Giabbanelli et al., 2017; Gray et al., 2015; Mourhir, 2020).

There are trade-offs associated with FCM, primarily a loss of explicit temporal and quantitative analytical capabilities as legibility and accessibility increase. Accessibility is particularly important as FCM can serve as a method for participatory modeling, defined by Voinov et al. as "a purposeful learning process for action that engages the implicit and explicit knowledge of stakeholders to create formalized and shared representations of reality" (Voinov et al., 2018). Participatory FCM studies are generally transdisciplinary, drawing on diverse knowledge and community member experience working with, living in, and managing complex systems. There is a long tradition of using diverse perspectives and expert judgement in a variety of academic fields, and FCM studies can expand traditional definitions of expertise to center community voices (Galafassi et al., 2017; Otway and Von Winterfeldt, 1992; Skjong and Wentworth, 2001; Teck et al., 2010). Transdisciplinary work is advantageous to addressing wicked problems as it bridges boundaries between disciplines and communities through collaboration and co-learning to further our collective understanding of complex systems and problem-solving capacity (Head and Alford, 2015; Hinrichs, 2012; Pettigrew et al., 2001; Weber and Khademian, 2008). While participatory work is more resource-intensive, as additional time and labor is devoted to design, communication, and collaboration, ultimately decisions are higher quality and legitimacy (NRA, 2008). It also closes the gap between theory and practice as engagement with multiple actors at different levels and scales is vital to implementing transformative solutions to wicked problems (Van de Ven, 2007; Van de Ven and Johnson, 2006; Willett et al., 2019).

Another challenging aspect of wicked problems is that individuals can struggle to make high-quality decisions due to biases and cognitive limitations like bounded rationality or mental ability to accurately manage complexity (Doyle and Ford, 1998; Gregory et al., 2012; Simon, 1957). One way to circumvent the limitations of individuals is to average or weigh together multiple FCMs into group models and/or a singular collective intelligence model (Aminpour et al., 2020; Aminpour et al., 2021; Gray et al., 2020). This process uses wisdom of the crowd and collective intelligence theories; Aminpour et al. (2020) and others showed that individual perspectives can be aggregated to accurately approximate real-world systems and facilitate effective decision-making (Aminpour et al., 2020; Arlinghaus and Krause, 2013; Gray et al., 2020; Woolley et al., 2010).

However, FCM is very much a developing field. There have been significant innovations to the field since the inception of FCM in the late 1980s, yet as recently as 2014 a methodological assessment found limited mathematical techniques for aggregation (Jetter and Kok, 2014; Kosko, 1986). Early studies simply added adjacency matrices of individuals then qualitatively validated the aggregated map, while others first weighted and/or grouped participants into sub-domains of specialized knowledge in order to maximize independence between groups (Nadkarni and Nah, 2003; Nii, 1986; Rantilla and Budescu, 1999; Rush and Wallace, 1997; Stylios and Groumpos, 2004). Ultimately, the goal of many modeling efforts is to create a parsimonious model that simplistically and accurately represents a real-world system (see Figure 3-1) (Jones, 1952; Plouffe et al., 2001).

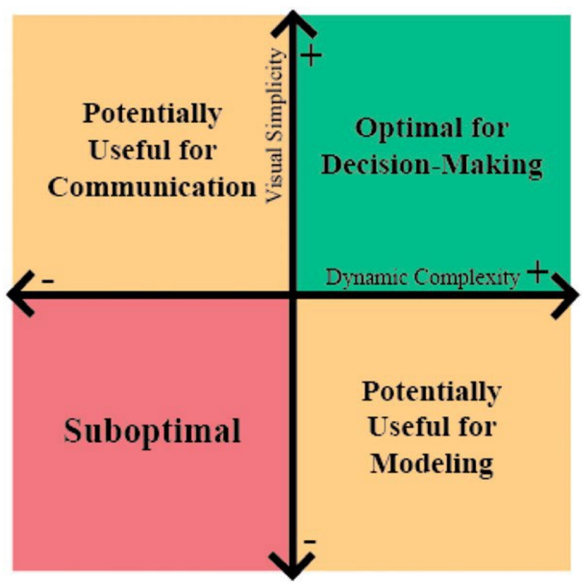


Figure 3-1: Four-quadrant chart showing the usefulness of FCM models based on visual simplicity and dynamic complexity.

Currently there are two main schools of thought about how to group individuals to create an effective collective intelligence model: utilizing identity diversity (Aminpour et al., 2020;

Aminpour et al., 2021; Gray et al., 2012; Schwermer et al., 2021) or cognitive diversity (Aminpour et al., 2021; Cholewicki et al., 2019). Identity diversity (surface-level diversity) is based on traits of individuals like social categories such as demographics, while cognitive diversity (deep-level diversity) refers to differences in cognitive traits like intelligence, attitudes, information, or values (Aminpour et al., 2021; Baggio et al., 2019; Phillips and Loyd, 2006). An abundance of research has evaluated the connection between and influences among surface-level identity and deep-level diversity, as well as how diversity impacts outcomes such as productivity, problem-solving, and decision-making (Chen and Kenrick, 2002; Hong and Page, 2004; Jackson et al., 1995; S. Page, 2007; Phillips, 2003; Williams & O'Reilly III, 1998).

Previous FCM studies have used identity diversity characteristics as a proxy for cognitive diversity, given the hypothesis that commonalities in social identities lead to shared experiences that influence knowledge and perception, and therefore an individuals' mental model (Aminpour et al., 2021). However, a more complex relationship between the two can cause identity diversity to be an imperfect proxy. Studies have shown heterogeneity in deep-level perspectives within a homogenous identity diversity group (Chatman et al., 1998; Phillips and Loyd, 2006). Further challenges to linking identity diversity and cognitive diversity arise from ambiguous delineation of social groups and/or multiple sources of knowledge and system understanding. Nevertheless, studies find that heterogeneous teams create more innovative solutions to problems and improved system management than homogenous counterparts, often due to the differences in cognition such as information and perspective (Baggio et al., 2019; Hong and Page, 2004; Jackson, 1991; Page, 2007).

Simply put, the critical conceptual difference between these aggregation methods rests in whether participants are grouped based on similarities in their social categories or the content of their individual cognitive maps. Currently, comparisons of these two aggregation techniques and discussion of the implications of those methods is lacking. Our primary research question is: what are the critical differences between, and advantages and disadvantages of, aggregating fuzzy cognitive maps based on identity and cognitive diversity? In this paper we test variations within the two aggregation techniques (see Figure 3-2) to determine which would be better suited for various types of research questions or study systems based on performance metrics like resource inputs, cognitive distance of groups, and similarity to the real-world system. In addition, we explore the challenges of and possible solutions to aggregating participants without discrete expertise groups. Specifically, this case study deals with participants with knowledge of multiple, overlapping food system sectors so cannot be grouped into a single type of expertise. Finally, we synthesize quantitative and qualitative findings of how aggregation techniques on a single dataset resulted in collective intelligence models of varying quality. This study fills a fundamental methodological gap by comparing aggregation techniques and providing guidance on an innovative method for combining knowledge from diverse experts to address wicked problems in complex systems.

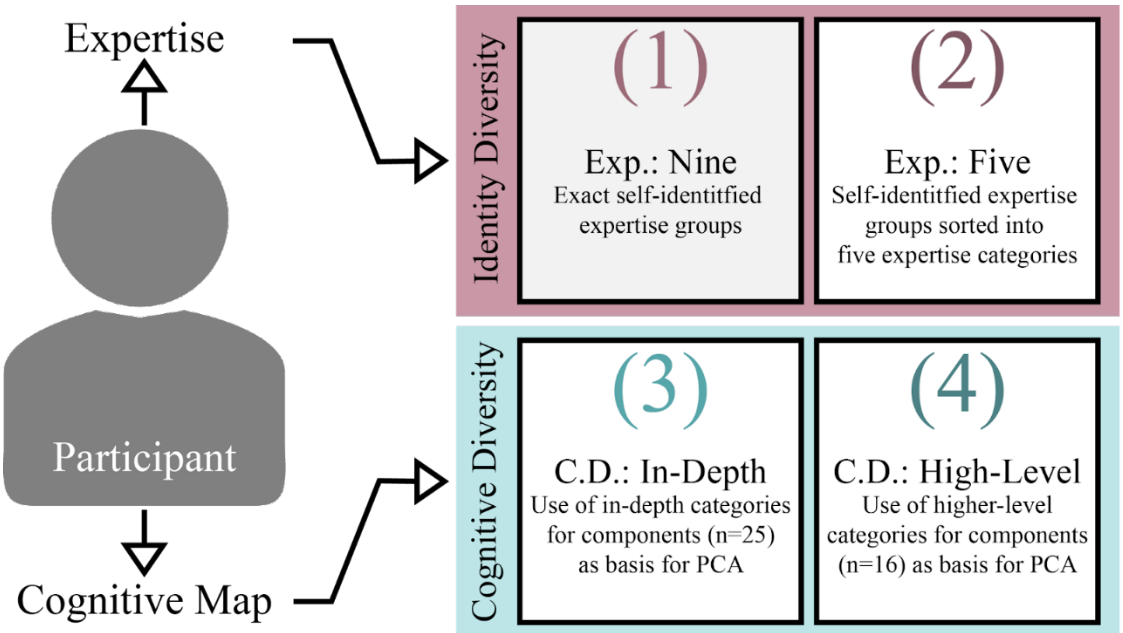


Figure 3-2: Illustration of four metamodel aggregation techniques, two based on identity diversity and two on cognitive diversity.

3.3 Methods

3.3.1 Data Collection

Food insecurity is a critical issue for many urban areas in the US, including Flint, Michigan. The complexity of the issue and the distributed knowledge of and decision-making power within the food system makes the study context an excellent candidate for evaluating the two aggregation methods. Structurally, the food system is an intricate mix of food provisioning and access points. Workshops with Flint community members and consultation with the Flint Leverage Points Project's (FLPP) advisory panel of community leaders. The Community Consultative Panel (CCP) heavily informed the development of the interview instrument (see Appendix A) in order to collect a diverse set of cognitive maps through one-on-one interviews. The focus of the modeling session interviews was "mapping" the Flint food system beginning with different sources of food in Flint and the “values” (see Appendix B), which were desirable food system outcomes as identified by Flint com- munity members during workshops (Belisle-Toler et al., 2021). Four primary food sectors were identified through consultation with the CCP and other Flint food system leaders: the retail, supplemental, emergency, and production sectors (see Table 3-1).

Table 3-1: Definitions of the food system sectors.

Food System Sectors:	
Retail Sector	Sells food to be cooked or is ready to eat (grocery and convenience stores, restaurants, etc.)
Emergency Sector	Provides food at no cost (food banks, soup kitchens, shelters, etc.)
Supplemental Sector	Nutrition supplement programs (WIC, SNAP, etc.)
Production Sector	Grows crops or rears livestock, can be at any scale from small gardens to large farms

We elicited study participants (N = 51) through snowball sampling, beginning with CCP members, by having each participant recommend up to three additional Flint food system experts. We used a broad definition of expertise when considering participants, including knowledge and experience from any source, including through formal work, unpaid labor (i.e., volunteering or activism), as well as through their lived experience. While some participants have focused expertise in a single sector and some have more broad expertise in several sectors, all hold expertise in the Flint food system. To address biases of snowball sampling, we also contacted influential Flint-based organizations, identified in a stakeholder analysis, or groups that were underrepresented or absent from the initial participant list provided by the CCP, such as convenience stores and local producers. However, Flint is a highly studied city and we found that personal referrals from our community partners and snowball sampling were more effective for participant elicitation than cold contacting.

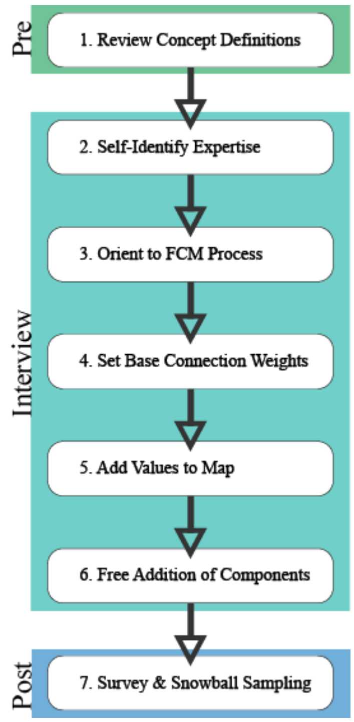


Figure 3-3: FCM interview process.

We elicited experts' cognitive maps through virtual semi-structured interviews using a seven-step process (Figure 3-3). The mapping interviews took between 60 and 90 min. Prior to the interview, participants were provided with a handout of base component definitions, which were also reviewed during the meeting to ensure common understanding of concepts (Step 1). At the beginning of the interview, participants self-identified their experience within the different sectors, listing how many years of experience they had, and stating if they were a Flint resident (Step 2). Interviewers oriented participants to the FCM process using a simple example to explain causal connections, polarity, and weight (Step 3). Participants began with a base map of the three sectors (see Figure 3-4) where they first determined the weights of the connections from "Use of Retail" to the five retail sub-sectors, and from "Use of Supplemental Sector" to the three retail store concepts (Step 4). While the fourth sector, production, was not explicitly part of the base map, participants could add a “Gardening + Local Agriculture” component at any time.

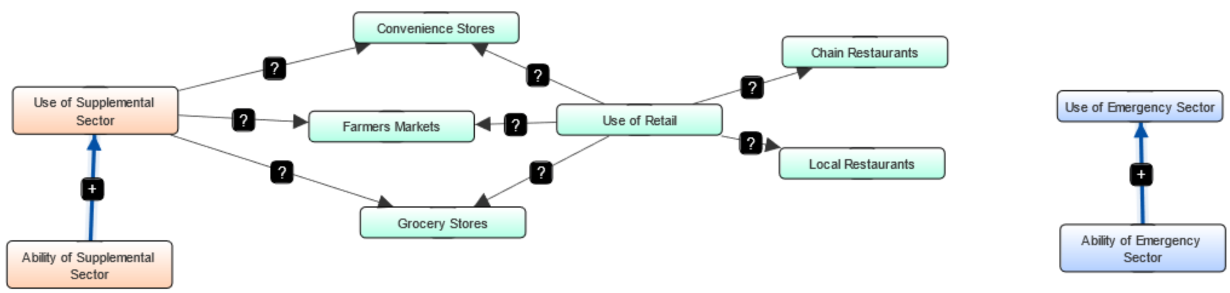


Figure 3-4: Base map of the interview.

Next, participants were asked to select from seven food system values, determined by workshops with Flint com- munity members (Belisle-Toler et al., 2021). Participants were asked to prioritize values that they have experience in or consider particularly important to add to their maps, which they then connected to the sectors (Step 5). For the rest of the interview, participants added any additional components or connections they perceived as important or influential to the Flint food system, which were semi- constrained to relevant topics by the interviewer (Step 6). Concept map creation followed established FCM data collection practices (Gray et al., 2014). The interviewer screenshared MentalModeler, an online fuzzy cognitive mapping software, to each participant and added components and connections based on the participants’ answers and directions. Participants routinely verified that the component names, connection direction, polarity, and weight were correct to their understanding of the Flint food system with regular prompting from the interviewer. Finally, participants completed a post-interview survey that collected demographic information and feedback on the modeling experience (Step 7).

3.3.2 Data preparation

To prepare the data for aggregation, we combined com- ponents with synonymous meaning. Standardizing concepts leads to easier aggregation and analysis (Gray et al., 2014; Jetter and Kok, 2014; Mourhir, 2020). Two researchers collaborated to reduce unique components not defined by the researchers (non-base components) based on conceptual similarity, based on the process of FCM standardization (Siqueiros-García et al., 2019). We used an inductive process as our decisions to combine concepts were made based on patterns in participant answers. For example, seven participants combined income and employment into a single component, so we grouped those and other participants' concepts like "Jobs," "Employment," and "Income" into the single component of "Income + Employment." Original maps were updated with the simplified, more consistent component names. Occasionally the polarity of connections was changed, in cases where the initial concept like "Unhealthy Food Choices" was grouped with the much more prominent "Healthy Food Choices" component. If two concepts were combined into a single component, for example, "Expired Food" and "Food Waste" within a single map were reduced to "Food Waste," connections were preserved and combined through addition as needed. Interview audio was transcribed using Otter.AI and was corrected and verified by a researcher for accuracy. Researchers coded each transcript using MAXQDA for descriptions of (1) novel components and (2) connections between components based on the participant's concept map. See Appendix C for a list of novel components.

3.3.3 Data analysis

3.3.3.1 Saturation

We calculated thematic saturation by deter- mining the number of novel categories within each individual cognitive map beginning with the first participant to find the point that all categories are represented (see Appendix D for categorization schemes). Due to the number of participants and scale of the interview topics, achieving saturation at the component-level is unrealistic because we largely left the concepts unstandardized, which is a trade-off in cognitive mapping (Gray et al., 2014). Concepts ranging from the micro to macro levels, for example, from individuals having microwaves in their homes to national immigration policy, can all have relevance to the Flint food system and be part of participants' cognitive maps. Thus, we used thematic saturation to determine if a comprehensive inventory had been collected. Achieving saturation ensures a holistic collective intelligence model as additional data collection (interviews with more participants) would likely not lead to the identification of additional categories (Guest et al., 2006; Saunders et al., 2018).

3.3.3.2 Aggregation based on identity diversity

One innovative method for aggregating individual cognitive maps into a collective intelligence model is combining the adjacency matrices of individual models by stakeholder or expertise group using the arithmetic mean of connection weights, and then aggregating group models using the median connection weight (Aminpour et al., 2020; Gray et al., 2012). This multi-step aggregation method has proved to result in parsimonious CI models when groups demonstrate diverse expertise (Aminpour et al., 2021). However, unlike previous FCM studies that had firm boundaries between stakeholder or expertise groups, we found a high level of expertise overlap between the different sectors (Gray et al., 2012; Schwermer et al., 2021). For example, one participant may have 4 years of experience working for a supplemental nutrition program, 6 years of volunteering at emergency food distributions, and have used the retail sector for the 10 years they have lived in Flint. To address this complexity, we used two different methods of grouping individual cognitive maps based on self-identified expertise (see Figure 3-5). The first method of grouping used the exact description of their expertise, resulting in nine expertise groups. The second method of grouping divided participants with a single expertise group into the four sectors and grouped participants with experience in three or more sectors into a multi-sector group. For participants with expertise in two sectors, their map was included in both groups. This results in five groups, four based on sector expertise and one for multi-sector expertise.

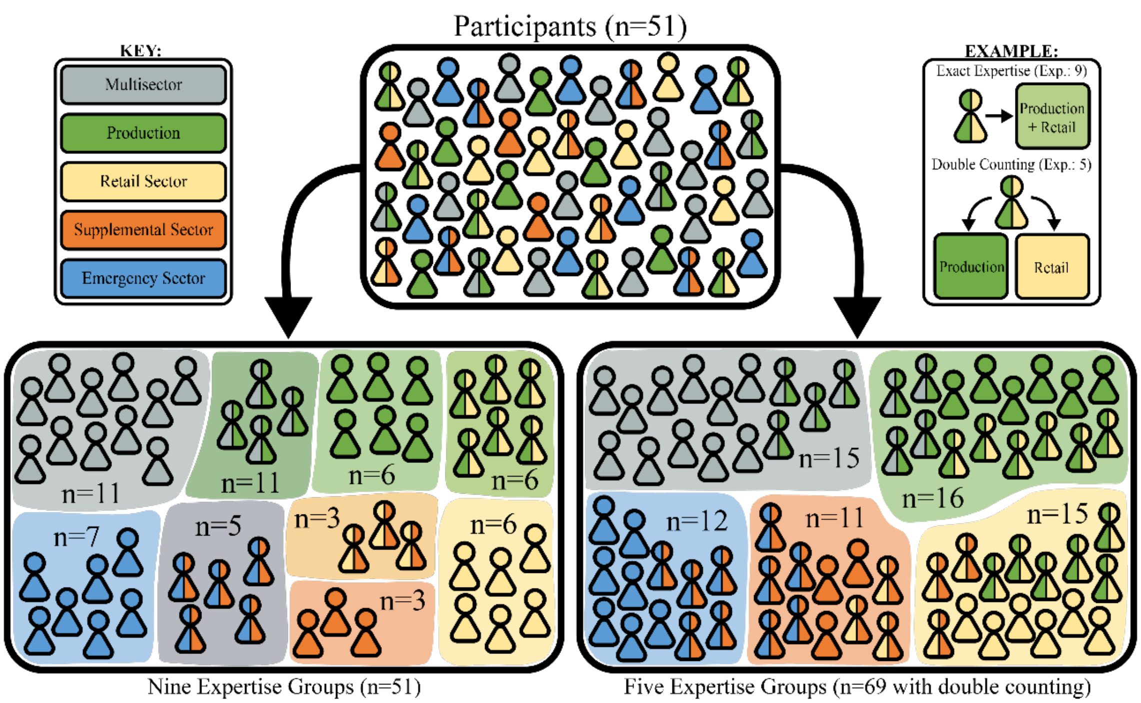


Figure 3-5: Comparison of participant groups based on expertise. The bottom left box shows grouping based on exact self-identified expertise group, while the bottom right box shows each sector, with participants in two sectors

being sorted into both expertise groups. A color-coding key and an example of how participants with multiple sectors of expertise would be categorized in each grouping scheme is included.

3.3.3.3 Aggregation based on cognitive diversity

A second, more data-driven approach to aggregation of individual cognitive maps is by categorizing components, conducting a Principal Component Analysis (PCA), and grouping participants based on cognitive diversity (Aminpour et al., 2021; Cholewicki et al., 2019). The goal of this type of categorization is to determine the major conceptual groupings of components which can be used to analyze the models and link participants based on conceptual similarities (see Figure 3-6). We explore two methods for emergent categorization: (1) a more in-depth scheme typifying components as firstly their function in the problem space (activities, drivers, barriers, and outcomes) and secondarily based on thematic similarities, and (2) a higher-level scheme organizing components based on the sector or element of the food system (see Table 3-5 in Appendix D).

A cornerstone of the categorization schemes was the values and sector definitions emerging from conversations with Flint residents and food system experts (see Appendix B). Also highly influential was Ericksen's conceptualization of the food system, which is used by the larger Flint Leverage Points Project (Ericksen, 2008). However, a small deviation was made away from using a "human capital" framing (Bowles and Gintis, 1975; Tan, 2014). Other sources, primarily in the sustainability or food systems space, were used to determine common terms in academic literature for drivers (Haddad et al., 2016; HLPE, 2017; O'Neill et al., 2014), outcomes (Keyes, 1998; Ostrom, 2009; WFS, 1996), and barriers (D'Este et al., 2012; Swanson and Tokar, 1991; Trianni et al., 2017; Truman and Elliott, 2019). Both categorization schemes were evaluated and validated by multiple researchers.

For each FCM a standardized sum of centrality (NSc) was generated for each category (Cholewicki et al., 2019). First, we calculated c_i as the weighted contribution of each component i.

$$c_i = \sum_{k=1}^{n} |a_k|,$$

where n is the number of connections a component has and a is the weight of each connection. Second, we determined Sc, which is a measure of the centrality of all components in a category.

$$Sc = \sum_{i=1}^{N*} c_i,$$

where N* is the number of components in a category. Then the Sc for each category was normalized based on the total Sc for all categories. We refer to this value as the weighted absolute degree centrality.

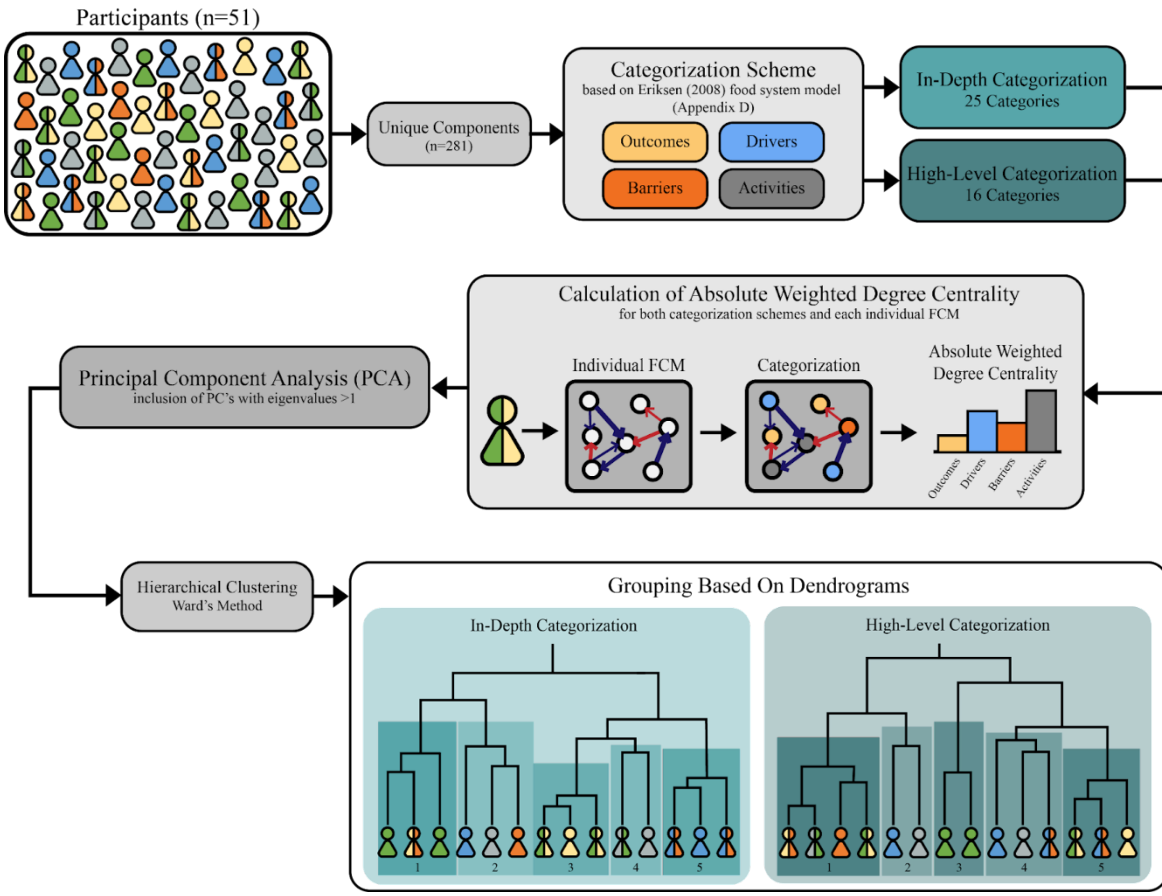


Figure 3-6: Visualization of process for creating a conceptual categorization scheme, use of scheme for calculating the absolute weighted degree centrality of each category, principal component analysis, and clustering based on the resulting dendrograms. For details on the categorization scheme and dendrograms, see Appendices D and H, respectively.

Using the weighted absolute degree centrality of the different categories, we conducted a Principal Component Analysis (PCA) in R (Jolliffe, 2002). Principal components (PCs) associated with eigenvalues greater than one were included, which represented more than 50% of the explained variance. Then, we reduced the number of dimensions and used the PC coordinates for hierarchical clustering by Ward's method (Ward, 1963). Hierarchical cluster analysis is a common method for grouping a set based on similarities among the items, in this case participant cognitive maps. Clustering correlated variables allows for the creation of a dendrogram, a kind of tree diagram used to visualize hierarchical clustering (Bridges, 1966). We used the dendextend R package to create dendrograms of each categorization schemes' PCA results, as well as tanglegrams which can be used to compare two dendrograms of the same set (Galili, 2015; Nöllenburg et al., 2009). The entanglement function was also used to calculate the alignment of the two dendrograms, with zero representing perfect alignment and one representing complete misalignment (Galili, 2015).

As there are relatively few observations, 51 participants in multidimensional space, calculating a useful number of groups can be challenging. For clarity, "clustering" is used both in the context of hierarchical clustering which produces dendrograms, and the process of clustering data or items into groups. For the purposes of this paper, we will refer to determining participant groups from a hierarchical cluster as "grouping." Common methods like the gap or silhouette statistics can be ill-suited for data without well separated clusters (Tibshirani et al., 2001). While there are more complex methods of determining a useful number of groups within high-dimensional data, one advantage of hierarchical clustering and dendrograms is the ability to visually assess the data (Bouveyron et al., 2007; Steinbach et al., 2004). Hierarchical clustering does not rely on a set number of groups, rather dendrograms can be "cut" at different levels which varies the number of groups (Steinbach et al., 2004). Aspects of the dendrograms such as stem height and researchers' subject matter expertise can effectively be used to determine an appropriate number of groups.

3.3.3.4 Metamodel creation

Once the participants are grouped, either by identity diversity or cognitive diversity, individual maps are aggregated into group-level models using the arithmetic mean of connection weights. Then, a single collective intelligence model was created using the median of group-level models' connection weights, as section 3.3.3.2 describes. See Figure 3-7 for a visual representation of the aggregation methodology.

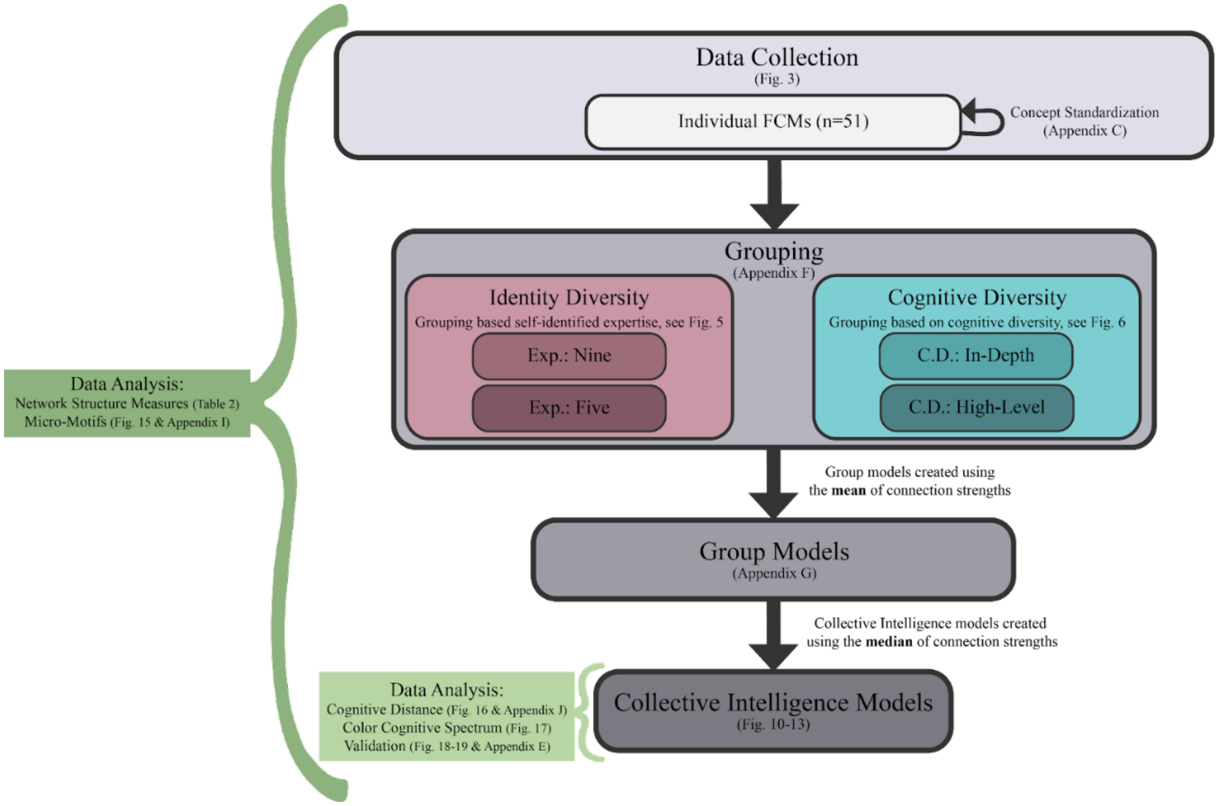


Figure 3-7: Visualization of methodology, describing the stages of data collection, concept standardization, grouping based on expertise and conceptual categories, aggregation, and data analysis.

3.3.3.5 Network Structure Measures

The following network structure measures were calculated for each participants' cognitive maps, group models, and the collective intelligence models:

1) *Total Components* (N) – number of components in a model.
2) *Total Connections* (C) – number of connections in a model.
3) *Density* (D) – number of connections as a proportion of the number of all possible connections.

4) *Connections per Component* (C/N) – number of connections as a proportion of components.
5) *Number of Driver, Receiver, and Ordinary Components* – total number of components with only outward connections (drivers), inward connections (receivers), or both (ordinary).

3.3.3.6 Micro-motifs

Micro-motifs, which are also called causal motifs of network substructures, are fundamental causal structures in networks that represent different dimensions of systems thinking (Levy et al., 2018; Milo et al., 2002). Compared to random networks of the same size and density, complex networks like the food system are found to have a significantly higher occurrence of complex micro-motifs (Milo et al., 2002). Micro-motifs have been used in FCM studies to compare levels of systems thinking across individuals and within aggregated models (Aminpour, Gray, et al., 2021; Aminpour, Schwermer, et al., 2021; Hamilton et al., 2022). Using the six substructures proposed by Levy et al. (see Figure 3-15), we determined the number of each micro-motif within the individual maps, group maps, and metamodel. For each FCM map, we counted the number of motifs in 1000 simulated random graphs of the same size and density (Levy et al., 2018). Specifically, we used the number of vertices and edges from the original graph as the basis for generating random sequences of out- and in-degrees, ensuring that each component had at least a degree of one and the resulting graph would have the correct density. See Github repository for information on the code. Once the 1000 simulated graphs were generated and micro-motifs counted, we calculated the probability distribution for each micro-motif for each set of graph dimensions.

3.3.3.7 Cognitive distance

One of the ways to compare FCMs is by calculating a network distance. There are many approaches to defining network distance that differ in treatment of connection direction and weight (Tantardini et al., 2019). In this study, we use "cognitive distance," introduced by Aminpour et al. (2021), which has been utilized to consider the direction and weight characteristics of each network. For clarity, cognitive distance is a metric that is calculated between networks, while cognitive diversity refers to the differences in how participants understand and think about the system. In this approach, the cognitive distance is the function of two separate network distances: (1) the Jaccard distance, which accounts for the direction characteristics of FCMs (Tantardini et al., 2019), and (2) a Euclidian distance between the subsets of eigenvalues of the normalized graph Laplacians constructed from the weighted, undirected network topology, which considers the weight characteristics of FCMs (Aminpour et al., 2021; Gera et al., 2018). The cognitive distance between every pair of metamodels was computed to explore cognitive distance across the data manifold. To provide deeper insights into how the cognitive distances of individual FCMs vary within or across groups (based on similarities in their social categories or the content of their cognitive maps), the average and standard deviation of the intergroup and intragroup cognitive distances have been calculated. A shorter intragroup cognitive distance average (standard deviation) is taken to represent a more homogenous group of cognitive maps, and conversely for a larger intergroup average.

3.3.3.8 Cognitive color spectrum

Cognitive Color Spectrum (CCS) is a visualization tool that has been utilized for the comparison of individual FCMs (Cholewicki et al., 2019; Hodges et al., 2019) and evaluation of cognitive maps across subgroups (Arroyo-Lambaer et al., 2021) based on the domination of predefined or emergent categories—demonstrating the pro- portion of each category in the individual FCMs. CCS uses network characteristics such as degree centrality (Cholewicki et al., 2019) or betweenness centrality (Arroyo-Lambaer et al., 2021) as a measurement for representing the proportion of each category. Each CCS can be demonstrated as a bar chart in that each color is representative of a unique category and the length of color is representative of the relative share of the centrality of each category in each FCM. In this study, CSS has been utilized to compare the four metamodels based on the high-level categorization (including 16 categories). Weighted absolute degree centrality (explained in section 3.3.3.3) has been selected to measure the centrality share of each category within each map.

3.3.3.9 Evaluation of metamodels

Community consultive panel (CCP) members and several other Flint food system experts who participated in modeling provided feedback through a survey to verify how the aggregated metamodels captured the Flint food system. The three dimensions of evaluation were as follows: (1) the components included in the model, (2) the proportion of the themes, and (3) the outcomes of scenarios. The survey questions asked participants to select what the best representation of the Flint food system would be, which we used to evaluate the performance of the four collective intelligence models. For more information about the survey instrument, see Appendix E.

3.4 Results

3.4.1 Data Collection & Preparation:

In total, 51 participants were interviewed. Participants had, on average, 10.25 years of experience with the Flint food system, and 82% were residents of Flint, MI. See Figure 3-8 for an overview of self-identified sector expertise. Through the concept standardization process, 469 non-base components were reduced to 281 novel components. This resulted in a total of 2613 connections across the 51 individual fuzzy cognitive maps. See Appendix C for a definition of each novel concept and the number of mentions across the individual cognitive maps.

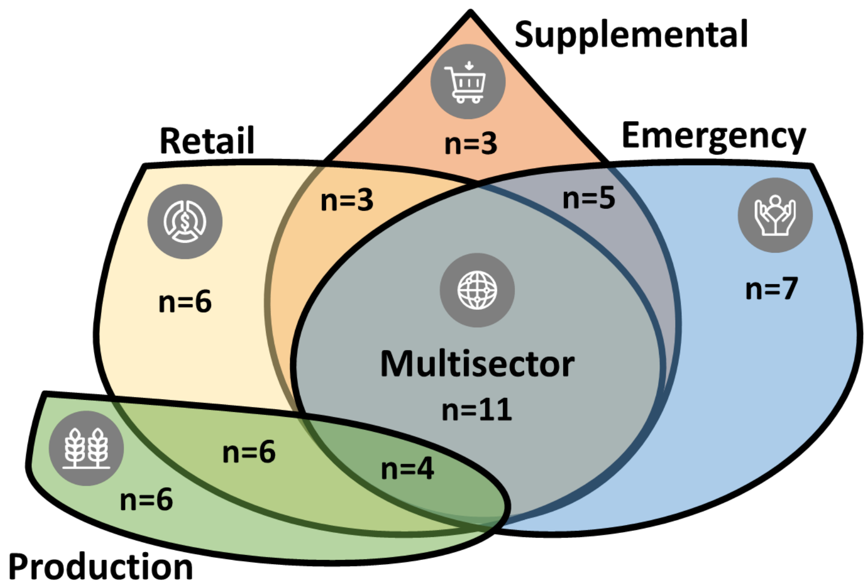


Figure 3-8: Self-identified sector expertise groups.

3.4.2 Data Analysis:

3.4.2.1 Saturation

The thematic saturation points were 23 and 12 participants for the in-depth and high-level categorization, respectively (see Figure 3-9).

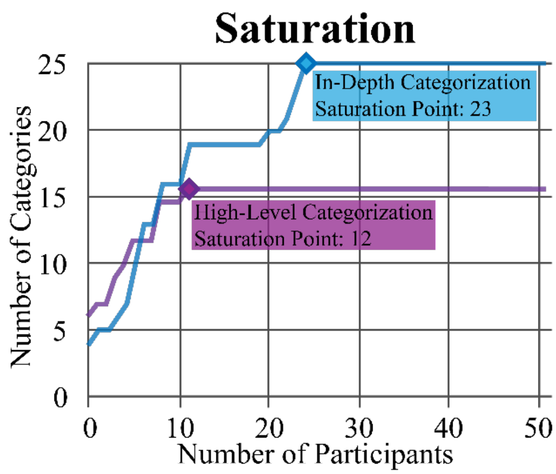


Figure 3-9: Saturation of categories based on in-depth (25 categories) & high-level categorization (16 categories).

3.4.2.2 Aggregation Based on Expertise

Aggregation based on expertise group led to the creation of two metamodels (see Figures 3-10 and 3-11). The expertise groups and group-level models can be found in supplemental information (see Appendices F and G, respectively).

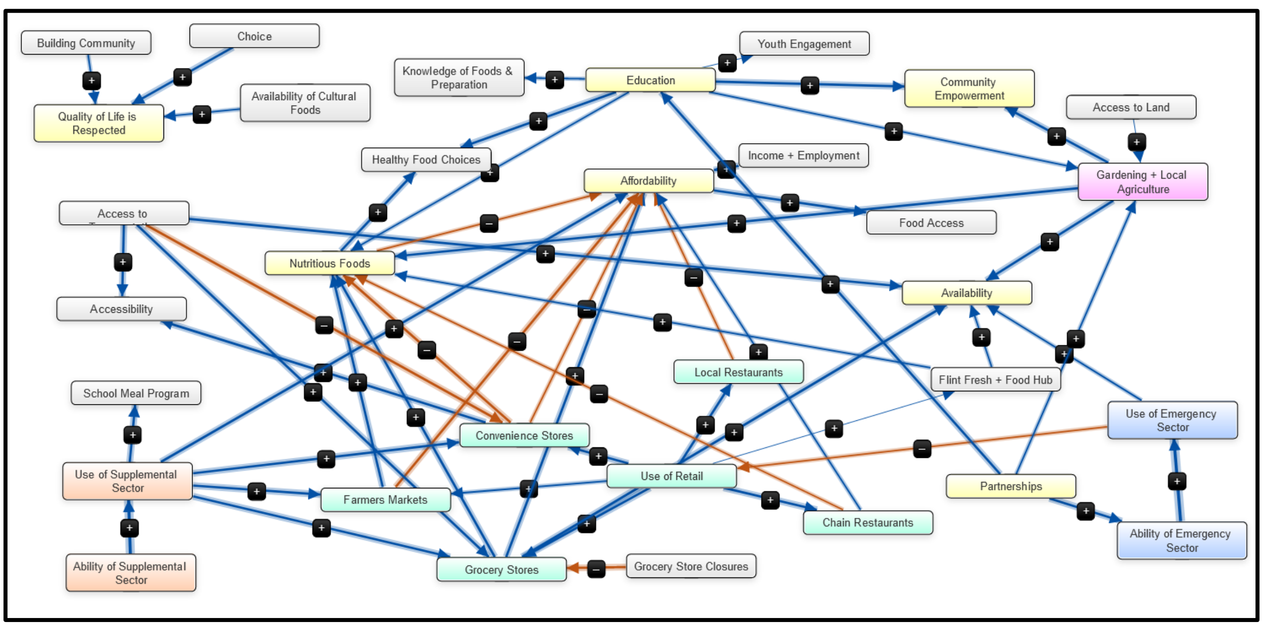


Figure 3-10: Metamodel from Nine Expertise Groups (n=51)

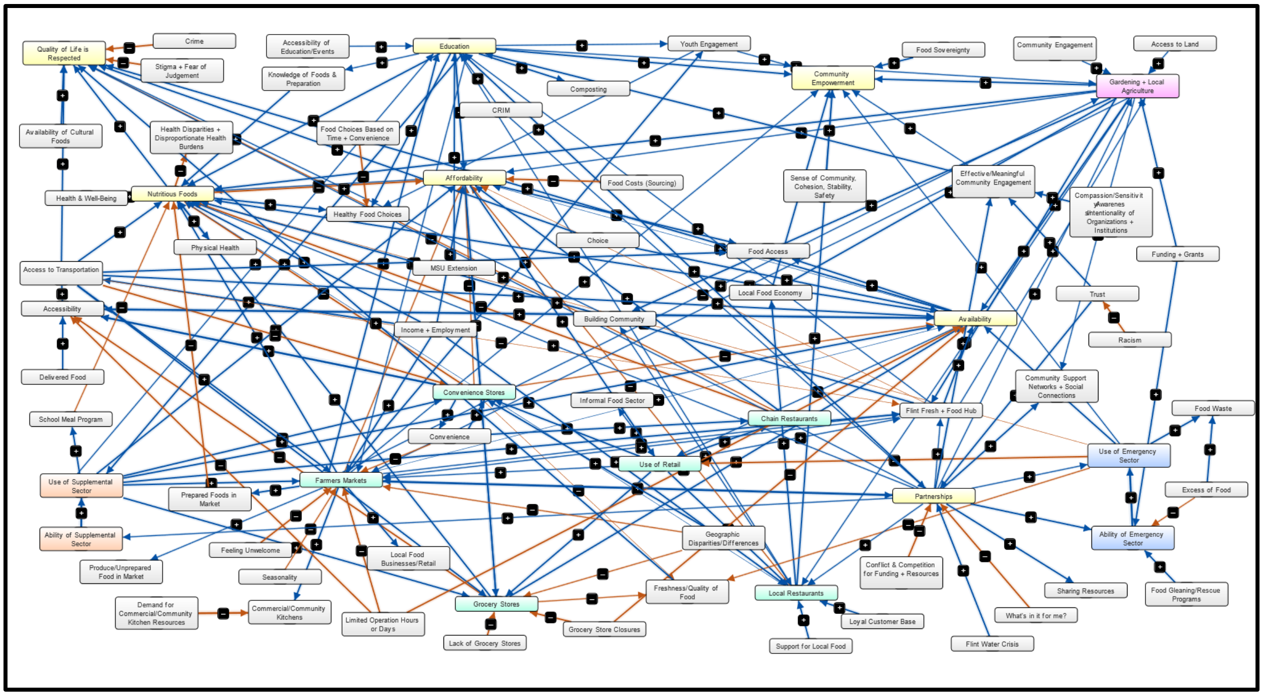


Figure 3-11: Metamodel from Five Expertise Groups (n=69)

3.4.2.3 Aggregation Based on Cognitive Diversity

Using the in-depth categorization scheme, the original 25 categories were reduced to ten dimensions which explained 73.6% of the variance. Then the histogram was used to determine the correct number of clusters, which is five for this data (see Appendix H). Similarly, the high-level categorization was reduced from sixteen to six dimensions, which represented 63.4% of explained variance. The number of groups for this categorization scheme was also five. Groupings were used to create metamodels (Figure 3-12 and 3-13). The group models for each aggregation technique can be found in supplemental information (see Appendix G). A tanglegram of both dendrograms was created and had an entanglement score of 0.58 (Figure 3-14).

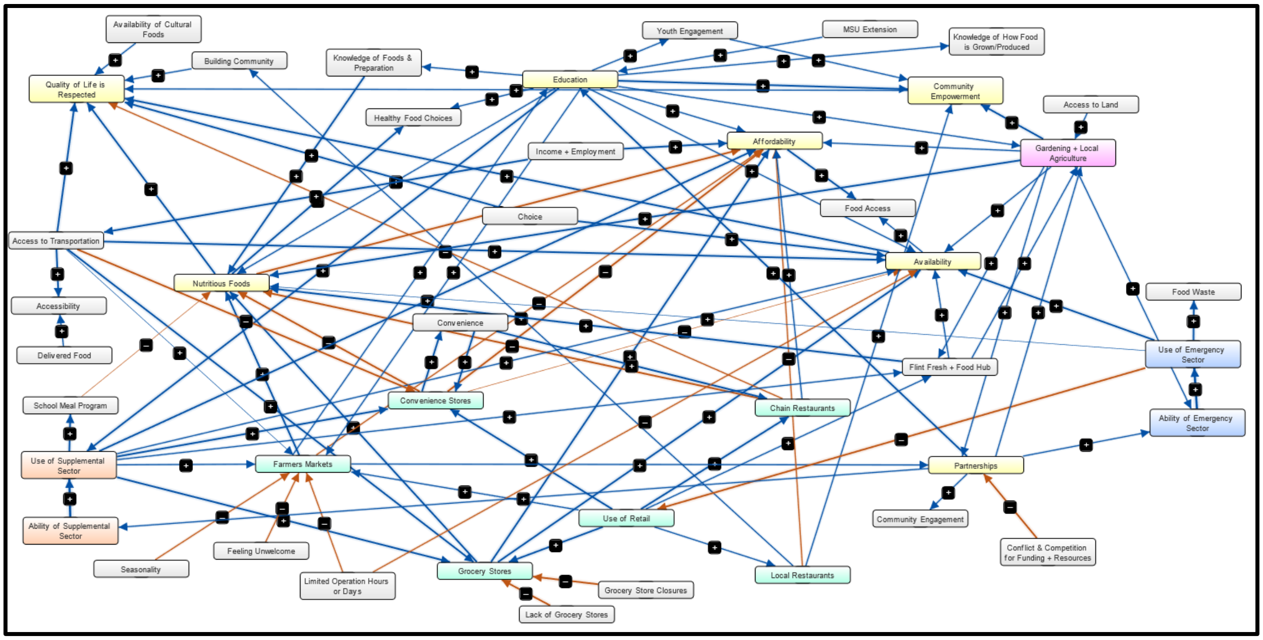


Figure 3-12: Metamodel from In-Depth Categorization (n=51)

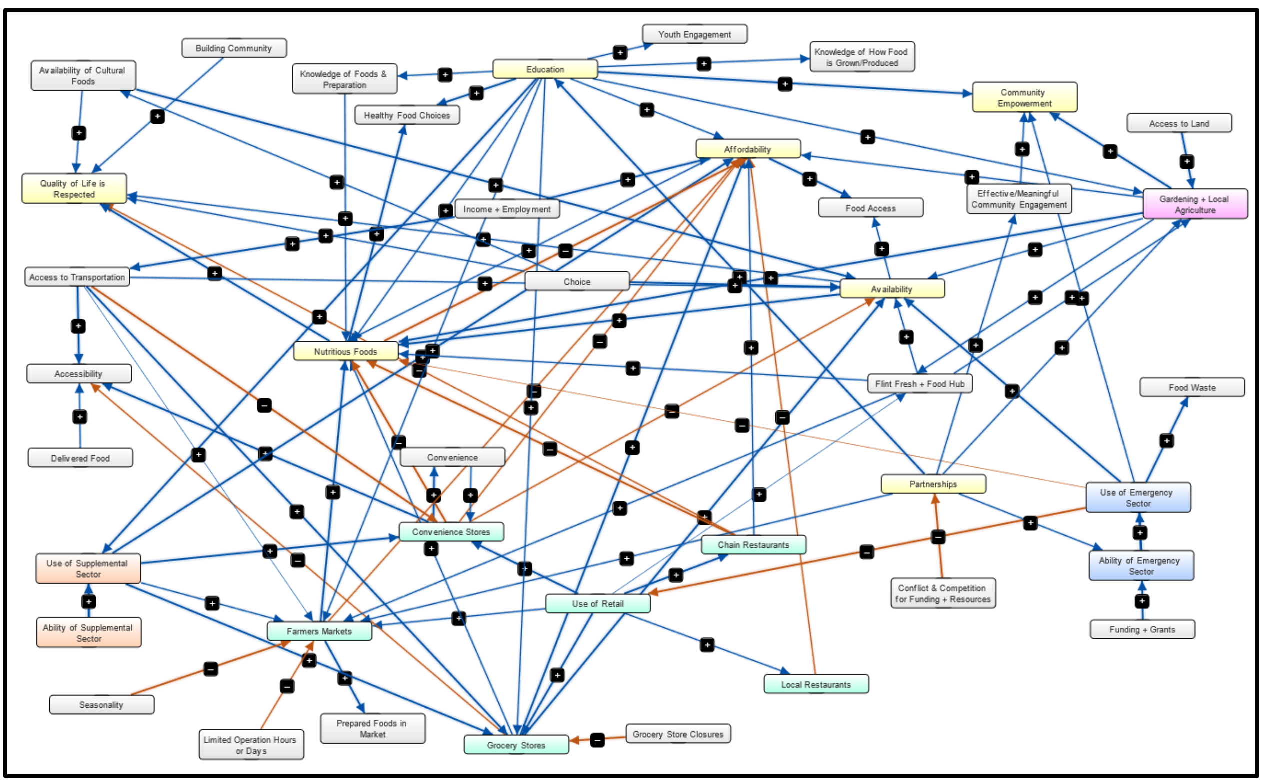


Figure 3-13: Metamodel from High-Level Categorization (n=51)

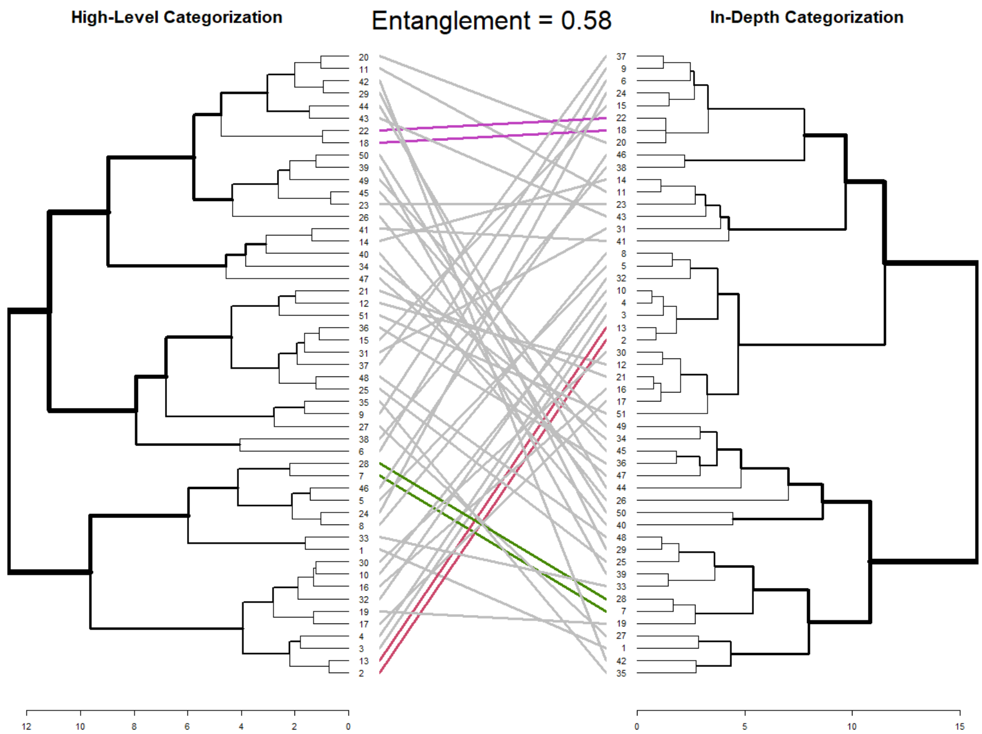


Figure 3-14: Tanglegram of hierarchical clustering based on PCA using high-level versus in-depth categorization. The colored lines indicate pairs grouped together in both dendrograms.

3.4.2.4 Network Structure Measures & Micro-motifs

The metamodel from five expertise groups is the largest, and least dense, with 76 components and 181 connections. The metamodel from nine expertise groups is the smallest network. The cognitive diversity-based metamodels have a higher percentage of ordinary variables than the expertise-based models. All network structure measures for the four metamodels are reported in Table 3-2.

Table 3-2: Network structure measures of the metamodels and average of the individual cognitive maps.

	# Maps	# Components	# Connections	Density	C/N	# Drivers	# Receivers	# Ordinary
Exp.: Nine	51	32	53	0.0534	1.66	9	9	14
Exp.: Five	69	76	181	0.0318	2.38	32	15	29
C.D.: In-Depth	51	43	96	0.0532	2.23	12	7	24

C.D.: High-Level	51	41	89	0.0543	2.17	11	9	21
Avg. of Individual Maps	51	28.7	51.3	0.0740	1.79	6.8	5.8	16
St. Deviation of Individual Maps	51	9.32	19.4	0.0347	0.315	3.2	2.7	7.2

Micro-motifs were detected and counted in the individual, group, and metamodels (see Appendix I for precise counts). In addition, the final number of motifs was compared to 1000 random sample connected networks of the same size and density to calculate the probability of the model having fewer motifs than was present (see Figure 3-15) (Hamilton et al., 2022). For example, if a metamodel had four instances of bidirectionality, the percentage of random networks with three or less of that particular micro-motif would represent the probability that the metamodel would have fewer network structures. Specifically, 100% and 0% mean that no random graphs had as high or as low a frequency of the motif, respectively. By comparing the network structures of the collected model to the distribution of micro-motif counts from randomly connected networks of the same size and density, we can draw conclusions about the complexity of the collected FCM.

In general, complex systems, like the Flint food system, are expected to have higher instances of micro-motifs than random graphs. We found that micro-motif prevalence varied across the metamodels, with Exp.: Five and C.D.: In-Depth having the highest prevalence. Both cognitive diversity metamodels followed similar patterns, but the identity diversity models were very different. Exp.: Nine had few complex micro-motifs like feedback loops, while Exp.: Five had many more than random networks of the same size. These differences are likely caused by the relative sizes and aggregation methods; as Exp.: Nine is a much smaller network with a lower

C/N score and was aggregated across more groups, so there are less chances for micro-motif dynamics to be preserved.

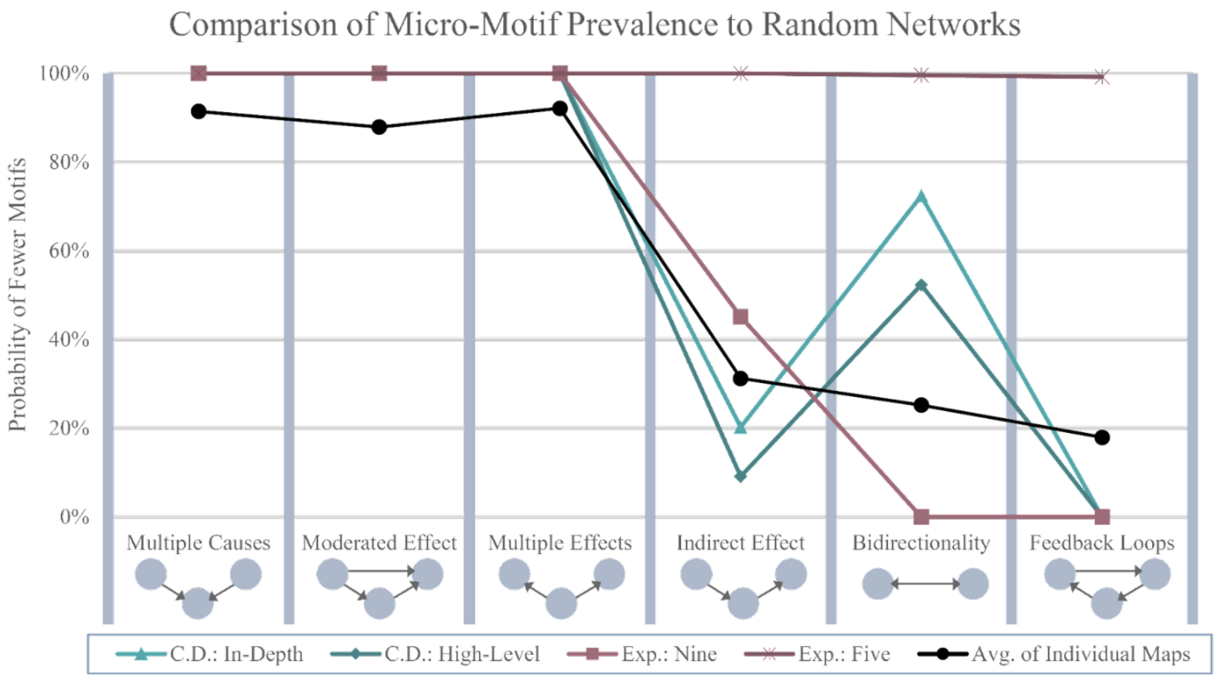


Figure 3-15: Comparison of Metamodels and Average of Individual Maps prevalence of micro-motifs based on the probability of random connected networks of the same size and density having less of the specific motif. Micro-motif figures adapted from Levy et al., 2018.

3.2.5: Cognitive Distance & Cognitive Color Spectrum:

To compare metamodels based on their network structures, the cognitive distances between each pair of metamodels was calculated. Figure 16 represents all the possible pairwise cognitive distances for metamodels. Each of the reported cognitive distances has been multiplied by a standardization coefficient for mapping to a normalized range from 0 to 1. The shorter cognitive distance represents greater similarity. As represented in Figure 3-16, "Exp.:Five" & "Exp.:Nine" metamodels have the longest cognitive distance, and "C.D.: In-Depth" & "C.D.: High-Level" have the shortest distance, demonstrating that the metamodels resulting from grouping participants based on the similarities in their social categories are considerably

different, from metamodels resulting from grouping participants based on similarity of individual cognitive maps. Therefore, using different methods for grouping the participants based on their expertise (five groups vs. nine groups) has led to structurally different aggregated models. In contrast, using different categorization schemes (In-Depth vs. High-Level) has resulted in structurally similar aggregated models. In addition, the aggregated model with nine groups of expertise is structurally closer to the aggregated models based on cognitive diversity rather than an aggregated model with five groups of expertise (i.e. the cognitive distances between the Exp.: Nine and aggregated models based on the cognitive diversity is shorter in comparison with the cognitive distance between the Exp.: Five and the aggregated models based on the cognitive diversity). Furthermore, since aggregated models are dependent on the grouping methods, the intragroup and intergroup cognitive distances based on the participants' social categories or their cognitive maps have been calculated to provide deeper group-level insights.
Intragroup/Intergroup distances are reported in Appendix J. Generally, the average intragroup cognitive distances are lower than the average intergroup distances for groups based on their cognitive maps. However, by grouping participants based on their expertise, a considerable number have higher average intragroup cognitive distances in comparison with average intergroup cognitive distances: four groups out of the nine groups of expertise and four groups out of the five groups of expertise have higher intergroup distances. This finding indicates a higher level of heterogeneity in the FCMs within groups of expertise based on the network structure assessment, particularly in the case of the “Exp.: Five” group.

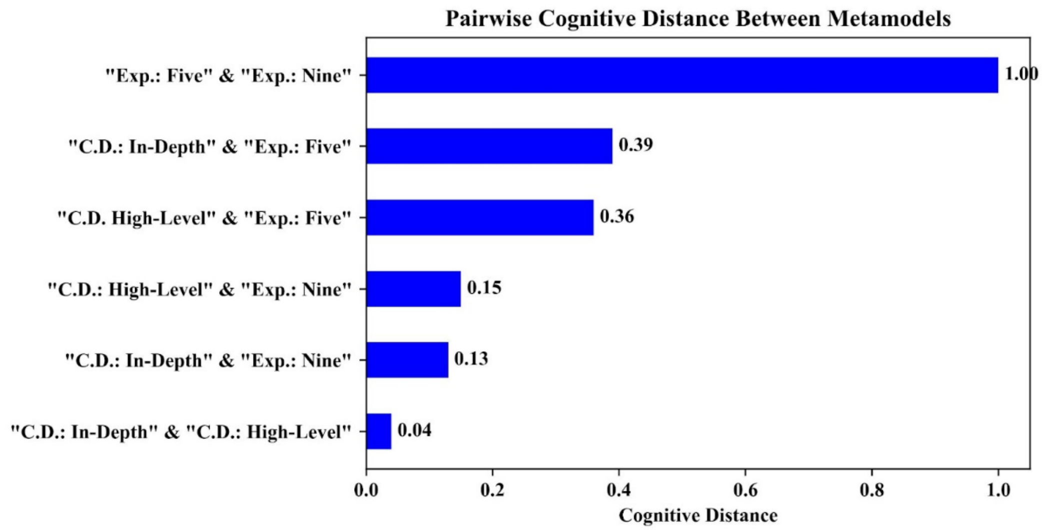


Figure 3-16: Calculated cognitive distance for each pair of metamodels.

Using the cognitive color spectrum tool, four different bar charts for each of the metamodels were produced to explore their similarities and differences contextually (Figure 17). Each color in the bar charts represents one of the sixteen predefined categories and the length of each color demonstrates the relative share of each category based on the weighted absolute degree centrality. As shown in Figure 3-17, the metamodels follow approximately the same contextual pattern regarding the domination of different themes. For all of them, “Retail Sector” and “Food Security Outcomes” are the most dominant themes (i.e. there are more components and connections in the metamodels related to these themes). On the other hand, themes including “Governance and Policy”, “Systematic outcomes”, Disposal and Waste”, “Community”, and “Economics” are less dominant (i.e. there are no or a few components and connections in the metamodels related to these themes). For a detailed definition of each theme, see Appendix D. Among all the metamodels, the metamodel from the five expertise groups (Exp.: Five) is the only metamodel that considered the “Governance and Policy,” and the metamodel from the nine expertise groups (Exp.: Nine) is the only metamodel that does not contain components or connections related to the “Disposal and Waste” and “Systematic Outcomes.”

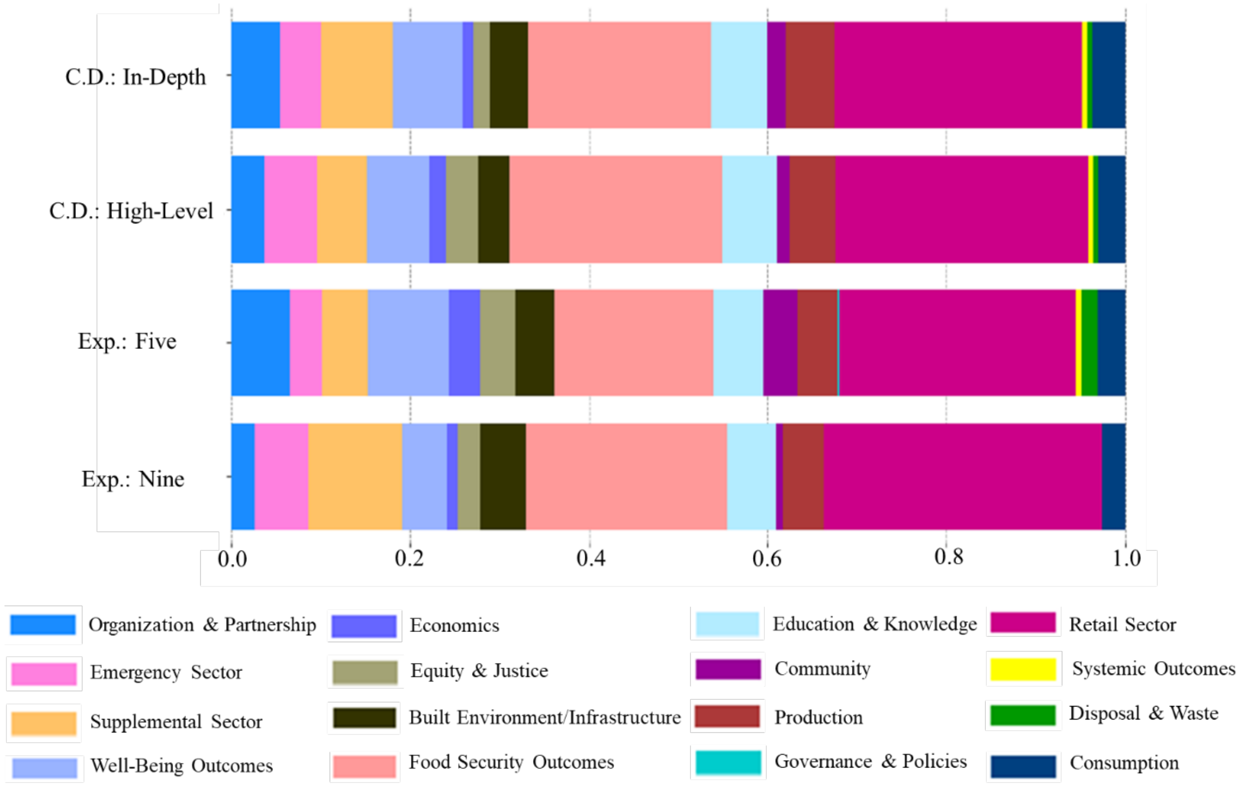
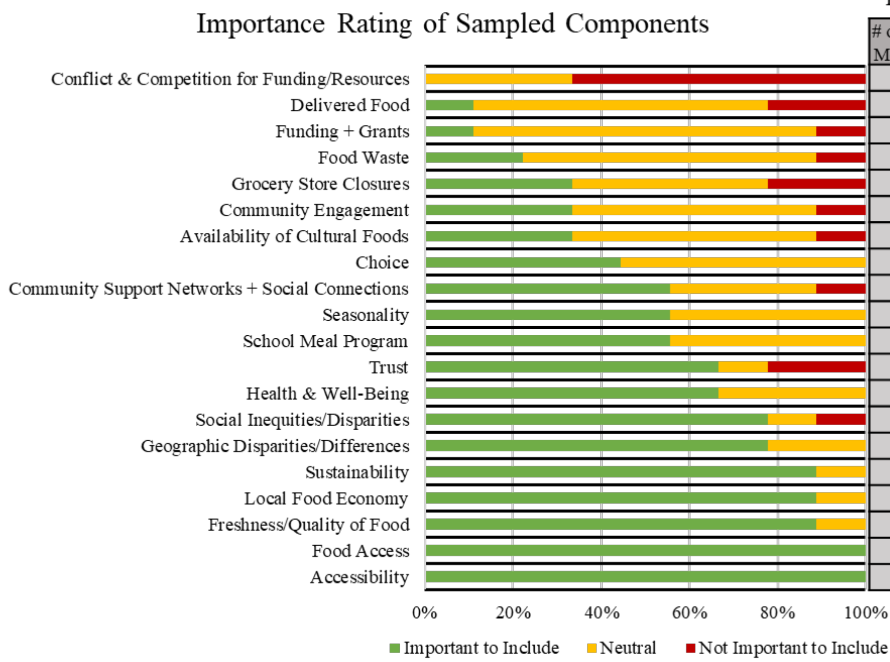


Figure 3-17: Cognitive Color Spectrum for each of the four metamodels. Each color is representative of a unique category and the length of color is representative of the relative share of the centrality of each category in each FCM.

3.2.6: Metamodel Evaluation

The metamodel evaluation survey was completed by nine participants. Of the random sample of novel concepts, eight of the twenty were rated as important by less than half of the participants (Figure 3-18). The metamodel from five expertise groups had the most components rated by the majority as important (10/12), with the other metamodels encoding only two. Interestingly, two highly rated components were not present in any of the metamodels, and eight components rated as neutral/not important by the majority were in at least two metamodels. For example, the “Funding + Grants” component was in fourteen individual maps and two of the metamodels but was rated mostly as neutral. This pattern shows an interesting difference in the concepts seen as significant in hindsight rather than those often discussed during modeling interviews.



Presence of Component in Metamodel

Component	# of Total Mentions	C.D.: In-Depth	C.D.: High Level	Exp.: Nine	Exp.: Five
Conflict & Competition for Funding/Resources	6	X	X		X
Delivered Food	4	X	X		X
Funding + Grants	14		X		X
Food Waste	13	X	X		X
Grocery Store Closures	7	X	X	X	X
Community Engagement	7	X			X
Availability of Cultural Foods	8	X	X	X	X
Choice	11	X	X	X	X
Community Support Networks + Social Connections	5				X
Seasonality	6	X	X		X
School Meal Program	6	X		X	X
Trust	9				X
Health & Well-Being	12				X
Social Inequities/Disparities	4				
Geographic Disparities/Differences	5				X
Sustainability	4				
Local Food Economy	5				X
Freshness/Quality of Food	8				X
Food Access	7	X	X	X	X
Accessibility	12	X	X	X	X

Figure 3-18: Importance rating of sampled components results from survey participants, compared to presence of component in the four metamodels (X in a green box means the component was part of the metamodel).

Considering the themes, the C.D.: High-Level metamodel had the highest verification to the Flint food system, with four "likes," five “neutrals,” and no “dislikes.” Exp.: Nine and C.D.: In-Depth had a ratio of 3-5-1 likes, neutrals, and dislikes, respectively. Exp.: Five had the lowest scores from participants, with two dislikes (see full results in Appendix E). The average predicted scenario outcome is compared to the metamodels’ outcomes in Figure 3-19. Comparing the total differences across scenarios, the order of performance from best to worst is

1) C.D.: In-depth, 2) C.D.: High-level, 3) Exp.: 9, and 4) Exp.: 5. See full calculation in Appendix E.

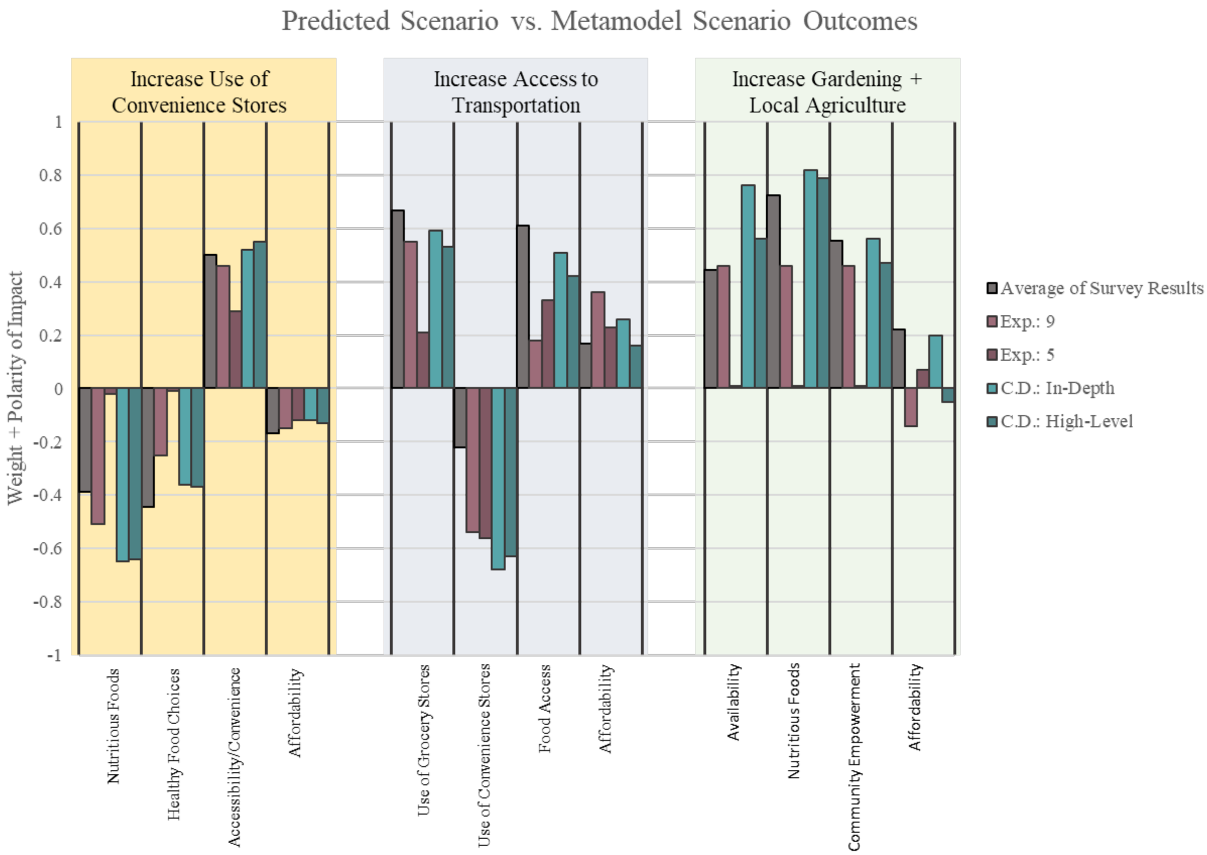


Figure 3-19: Comparison of the average outcome of scenarios predicted by survey participants and the actual scenario outcome values of the four metamodels.

3.5 Discussion

3.5.1 Technique Comparison

Comparing the two metamodels based on expertise groups, the most obvious differences are in size. The effect of "double counting" some participants to create five expertise groups was an overrepresentation of components which led to a very large map. For example, if only two participants mentioned a component, but both were double counted into four different groups, then that component would be present in the metamodel. In contrast, splitting participants into nine, small groups meant that at least five participants must mention a component, and potentially more if multiple were in the same expertise group. In that sense, aggregating with nine expertise groups led to an underrepresentation of commonly mentioned components. For communicating results to participants and/or community members, a concise model with a limited number of concepts is advantageous, so aggregating with a higher number of expertise groups may be preferred depending on the research question and context, as the process creates a metamodel with absolute core concepts and connections. However, there is also a loss of model complexity, which is evidenced by the disconnected cluster centered around the "Quality of Life is Respected" component (see Figure 3-10). This is unexpected as the vast majority of participants' FCM networks were fully connected. In a case where preserving complexity is preferred, aggregating with fewer groups is advantageous.

For the cognitive diversity metamodels, one difference is the saturation point. The high-level categorization scheme hit saturation at 12 participants, while the in-depth categorization scheme took 23 participants. This is unsurprising, as the key difference between the two schemes was the number and depth of dimensions to compare individual maps. Further evidence of the outcome of the categorization scheme is the tanglegram and final grouping. The two dendrograms have an entanglement factor of 0.58, which means that there is more misalignment of paired participants than alignment. Just under 50% of the participants were sorted into the same final group. Using simple linear regression to calculate a correlation coefficient for group membership, the two cognitive diversity groupings have a moderate correlation of 0.407. Comparatively, the nine groups based on expertise has correlation coefficients of 0.234 and 0.116 with the in-depth and high-level categorization groups, respectively (see Table 3-9 in

Appendix F for a full breakdown of group membership). However, despite categorization differences that lead to two different groupings, the cognitive diversity metamodels have similar components and connections. There are relatively small differences between the two metamodels, which speaks to the influence of a few key categorization dimensions being very influential, and that the addition of more categorization depth has a relatively smaller influence on the ultimate model composition. Given this finding, we recommend that researchers and practitioners prioritize determining key dimensions or conceptual categories for their data. In this case, a more detailed and labor-intensive categorization scheme did inherently improve the metamodel.

3.5.2 Performance Metrics

We can use network structure measures and micro-motifs as dimensions to evaluate how well the metamodels fit the expectations of complex systems. Generally, we would expect that complex systems have a comparatively higher density and lower C/N (Eden et al., 1992; Hage & Harary, 1983; Özesmi & Özesmi, 2004). Micro-motifs are also expected within complex systems, with higher numbers of simple structures like multiple causes and moderated effects, and comparatively lower counts of complex structures like bidirectional effects and feedback loops (Levy et al., 2018). This is not a universal rule so researchers and practitioners should use their knowledge, relevant literature, and other sources of system understanding to establish expectations for the specific system under study. The high-level cognitive diversity and nine expertise group metamodels performed best based on density and C/N, while the in-depth cognitive diversity and five expertise group metamodels had higher instances of micro-motifs.

Levy et al. found that more complex causal structures were underrepresented in experts' maps, a finding that is reflected in this study (see Table 3-10 in Appendix I) (Levy et al., 2018). In general, the micro-motif count within the individual maps decreased in-line with Levy's findings of micro-motif prevalence (e.g., a common micro-motif like multiple causes has a probability of 91.4% while more complex motifs like feedback loops has a 17.9% chance) (Levy et al., 2018). In contrast to Hamilton et al. (2022)'s finding of more feedback loops in aggregated cognitive maps than individual maps, we found very few feedback loops in the aggregated maps. This difference is likely due to dissimilarities in aggregation methodology and the modeled system. The large number of concepts, reflective of the multiscale system being modeled, made it unlikely for feedback loops to be preserved in the aggregated metamodel. Many participants modeled complex system dynamics through mediating components that "fell out" during aggregation. One area for further study would be techniques for preserving connections during the aggregation process.

To compare the four metamodel network structure and their contextual composition, "cognitive distance" and "cognitive color spectrum" tools have been utilized. By calculating the pairwise cognitive distance between every two metamodels, aggregated models were sensitive to the selected grouping method based on their expertise (longer cognitive distances); however, aggregation based on different categorization schemes was not very influential (shorter cognitive distances). Therefore, researchers using a top-down approach for creating aggregated models need to consider that social group or expertise may be a poor proxy for structural similarity of cognitive maps. When using the bottom-up approach for creating metamodels, we found that different categorization schemes may not lead to structurally different aggregated models. This may be due to key components within a few categories being highly influential to participant grouping, despite differences in categorization schemes. In general, comparing the intra-/intergroup cognitive distances (that considers the 281 components and all the possible connections between the components separately) confirms that PCA has grouped participants with similar cognitive map structure.

Despite metamodels having considerable differences in their network structure (such as the number of components, number of connections, and pairwise cognitive distances), different aggregation techniques have resulted in almost contextually similar metamodels that cover most of the predefined themes (regarding the cognitive color spectrum bar charts). For each of the four metamodels, "Retail Sector" and "Food Security Outcomes" are the dominant categories, which is unsurprising as many base components were in those categories. One takeaway from this result is that using different aggregating techniques can lead to the creation of structurally different cognitive maps, but the collective intelligence model still contains the major themes identified by participants (see Figure 3-20, in Appendix E). The critical differences are generally the less frequently mentioned themes.

3.5.3 Metamodel Evaluation

While aggregating using five expertise groups and double counting participants led to the largest map with the most components, this metamodel was generally validated as the least similar to the Flint food system in terms of themes and scenario outcomes. A high number of components, and particularly presence of components that are perceived as important to depicting the food system, enables more detailed discussion of dynamics and more possible scenarios. However, the larger metamodel performed the worst for scenario outcomes, which could be the product of a few different things. First, the additional components and connections could be clouding or diluting critical system dynamics. Second, double counting could be amplifying incorrect perceptions of system dynamics by overrepresenting some interview participants. Regardless, the metamodels aggregated using cognitive diversity were validated as the most correct for both the scenario and themes section, with the in-depth categorization scheme performing the best overall. In general, the qualitative evaluation of themes seemed to be the least accessible way for community members and experts to compare metamodels.

3.5.4 Limitations & Considerations:

There are several key limitations of this study. First, consider the grouping of participants into multiple expertise groups. Group membership can be contrasted easily between the other three metamodels, but the "double counting" of participants makes it impossible to directly compare them. Secondly, when calculating cognitive distance, all the connection weights have been assumed to be positive despite the cognitive maps containing negative connections. Therefore, other methods of calculating network distances should be considered and developed (Tantardini et al., 2019). Approaches deriving from recent developments in graph signal processing (GSP) and graph neural networks (GNNs), which leverage correlations among multiscale features on non-Euclidean domains, form a promising line of research into FCM and complex systems modeling more generally. Such methods expand the space of network features which, perhaps counterintuitively, enables more nuance in the comparison, clustering, classification, and communication of such. The merits of these methods have been demonstrated in the analysis of protein networks, the *C. elegans* neural connectome, and social networks (Brugnone et al., 2019; Gao et al., 2019; Zhang et al., 2021). Natural extensions of these methods will enable researchers to employ far more of the information in each cognitive map in comparison, for instance, of those of varied size. Associated theory (from, e.g., the scattering transform literature of Perlmutter et al., 2019, and Bruna & Mallat, 2013) should further enable the identification and reduction of researcher bias in these contexts, while simultaneously increasing their specificity and range of use. There is great potential for insight into complex systems like the Flint food system via the overlap of perspectives in FCM and GSP.

One consideration for interpreting the results is the number of novel concepts. With almost 300 components, comparison of individual models can be difficult. While it was important for this specific system to preserve details to inform the creation of detailed sub-models, further concept standardization using broad terms would shift how individual models are compared and the resulting metamodel. As previously discussed, there were relatively few feedback loops in the metamodels which would likely increase with fewer components. Another consideration is the nature of the expertise pool, as the participants of this study naturally have unclear delineation in expertise or stakeholder group. It is impossible to have knowledge of a food system that exists in a vacuum, as we all bring sociocultural experiences with and perspectives on food into discussions. In a different system with more distinct roles or types of experience, identity diversity might serve as an adequate proxy for cognitive diversity.

3.5.5 Model Selection

Considering all the above factors, which is the "best" metamodel? Unsurprisingly, there is no simple answer. There are three key dimensions when considering the value of a model: 1) the fit for the system and use, 2) the similarities to a complex system, and 3) the accuracy to the real-world system being studied. One consideration is the constraints on the study, for example the amount of time, resources, and expertise available to the research team, as well as urgency for results. Categorizing components to determine cognitive diversity can be a time-intensive process depending on the number of components and relies on subject matter expertise by researchers. The PCA process also requires a level of quantitative proficiency. Especially in a study with a fast deadline, for example in the case of a shock or crisis, aggregating by self-identified identity diversity would be a much quicker process. A second consideration would be the audience; who is learning from and/or using the information generated by the model? In general, FCMs can be developed and communicated largely in lay terms and with simple logical heuristics that are fairly intuitive and easy to understand. If results are going to be shared with community members who have not been privy to the modeling process, a more simplistic model with fewer components and connections will be a better communication tool.

Aggregation methods can also be informed by the goals or purpose of the research. If the goal is to model the real system, or to inform a quantitative modeling technique, a more complex, difficult to visually interpret model may be appropriate. Depending on the research questions, it may be more or less important to achieve a model that reflects complexity or similarity to the real-world system. Markers such as network structure measures, micro-motifs, themes, and scenario outcomes are less relevant if the goal is to compare the knowledge and understanding of specific stakeholder groups, or if FCM is being used as a tool to facilitate discussion. In sum, there is a key trade-off between model size and complexity, as model size and density rise, legibility decreases. However, a more complex system enables more analysis options for running scenarios and is often needed to accurately capture system dynamics. For the purposes of the Flint Leverage Points Project, aggregating by cognitive diversity using the in-depth categorization scheme was selected due to the balance between visual legibility and complexity, and how the model captured the Flint food system when validated alongside other research results. While the model is not as accessible as the metamodel generated by using the nine expertise groups, the complexity is needed to explore a variety of scenarios based on leverage points, which is the ultimate goal of the project. A smaller model is not sufficient for the primary need, so extra effort can be put into explaining and breaking down the final aggregated model to overcome the negatives of that tradeoff.

3.6 Conclusion

Fuzzy cognitive mapping and the aggregation of individual maps into a collective intelligence model can be applied to many socio-environmental systems. Participatory modeling using FCM can improve the outcomes of modeling efforts in several ways: (1) modeling can follow an equitable engagement process to incorporate diverse knowledge sources for a more holistic understanding of systems, community knowledge, and values, (2) the products of participatory modeling can be improved system understanding, communication tools, and exploration of interventions to support decision-making, and (3) decisions based in participatory modeling can be high-quality with more acceptability, as stakeholders were directly involved and the decision-making process is more explicit and transparent (Aguilar, 2005; Gray et al., 2012; Gray et al., 2015; Gregory, 2000; Mourhir, 2020). The gap in FCM methodology we addressed is an analysis of how best to aggregate individual maps to help achieve these desirable outcomes. We conclude that aggregating by expertise group, or another marker of identity diversity, is ill-suited for modeling real-world systems with diverse knowledge holders. In those cases, double counting participants or creating many groups results in under- and overrepresentations of components. Developing a categorization scheme as the basis of aggregating by cognitive diversity is extremely influential, and analysts should ensure that key categories are appropriately reflected.

Ultimately, researchers and practitioners should carefully consider the trade-offs with resource inputs, communicability, and complexity when deciding what is the most appropriate aggregation technique that meets the needs of their work and the nature of the specific system. Methodological innovations for FCM are constantly expanding, which increases the possibilities for where and how FCM can be applied. To address societal issues like food insecurity, we need tools that take systems lenses and engage stakeholders to deepen our understanding of systems, evaluate interventions, and implement effective leverage points. FCM offers an accessible and flexible method for participatory research that can combine diverse perspectives to accurately represent complex systems and provide a basis for equitable decision-making. A core challenge of wicked problems is the inextricable link to complex socio-environmental systems, which makes tools for systems work vital to ensuring a sustainable future.

3.7 Appendices

3.7.1 Appendix A: Interview Instrument

Research Summary: We want to understand how the Flint food system, specifically the (a) emergency, (b) supplemental, and (c) retail food sectors, may impact various values identified through workshops with community members. Additionally, we want to know how COVID-19 has impacted the food system in Flint.

[Introduction to Interviewer]

Informed Consent:

The informed consent document explains the research and its purpose, that all of your responses will be confidential, any risks or benefits of participating, which is pretty minimal, as well as saying that your participation is completely voluntary. I'd like to record these sessions. The recordings will not be shared outside our research team and are for the purpose of helping ensure we capture everything you're sharing today. Would it be okay if we recorded this meeting?

Thanks for permitting me to record our interview today. The recorder is now on. As a reminder, this conversation is part of our Flint Leverage Points Research Project. Your participation is voluntary, and you can choose not to answer any questions or withdraw from this research at any time. We will keep this recording confidential within our research team and won't use or share your name or identifying information in any of our research results. However, please be mindful of anyone who might be in the room with you or nearby and able to hear your comments. You can follow up with any questions by emailing me, you have my email at. Your consent is demonstrated by your continued participation in this interview. Do you have any questions about this before we move forward?

Section 1: Expertise

Q1: How would you describe your role or multiple roles within the Flint food system?

Q2a: RESIDENT: Are you, or have you ever been a Flint resident?

- How long have you lived in Flint?

Q2b: EMPLOYMENT: So, you mentioned that you worked at/for [name], how long did you work there?

- Did you have other roles there? [If unclear, how many years?]

Q2c: UNPAID: And for the [volunteer work or unpaid work], how long have you been involved?

- Are/Were there other responsibilities you have/had there? [If unclear, how many years?]

[Definitions of Sectors]

Q3: Based on what we just discussed; how do you think about your expertise within the three different sectors? Where do you see yourself having the most expertise?

Section 2: Modeling

Okay, so now we are going to move on to the modeling part of this interview. I will switch screens to the modeling software and give a brief explanation of the modeling process. The software we will be using is called MentalModeler, which was developed as a tool to capture peoples' knowledge and understanding of systems. It's also free to access online.

We're hoping to do a lot of these interviews, get a lot of maps from people, and combine them to basically find a common understanding of the system. Different people think about the system in different ways, and we want to look at where there is overlap. The goal of this interview is to capture how **you** think about the **current** Flint food system. There are absolutely no wrong or right answers.

[Introduction to MentalModeler and FCM using an example about traffic and transportation]

As I said before, there is no wrong or right answer, just what you think. I will also probably ask some clarifying questions, but those will always be to make sure that I am correctly interpreting what you are saying, not that I doubt or don't agree with anything.

Next, I will switch to a map that already has the three sectors we talked about earlier. Before we go into the mapping process, I want to walk through the connections that we have already made and see what you think about the connection strengths.

Starting with the use of retail to the different types of retail, you can think about the strength of these connections as measuring like "of the retail food sold in Flint, how much of it comes from the different types of retail?"

Q4a: How would you describe the different connection strengths between retail use and the five retail types?

Q4b: Okay, then thinking about the connection strengths between use of the supplemental sector and the different types of stores, how do you think about these strengths? Are supplemental nutrition programs used at certain places more often in Flint?

There is also a strong positive connection between the ability of the emergency and supplemental sector and the use of each sector because that impacts the amount of food people can get from each source. Do you have any questions?

[Definitions of Values]

Q5: Which of these other values are important to the Flint food system that you want to include in your map?

- Consider which 2 or 3 are the most important, add them to the map

Q6a: Based on how you see the current food system in Flint, how would you draw connections between these concepts?

Probes:

- Tell me how you see the relationships between the three values?
- Describe any connections you see between the three sectors?

Check-In Prompts:

- Okay, so what I heard is a [XYZ] connection from [Q] to [R], is that correct?
- Would you describe that connection from [Q] to [R] or [R] to [Q]?
- Do you think that is a positive connection or a negative connection?
- So for that connection, do you think it is a strong, medium, or weak connection?
- Is the connection I just added correct?
- Great, so how would you turn what you just talked about into a connection? From what node to which other node? Is it positive or negative?

Encourage participants to explain each connection, give the context. Especially if they are not sure about the polarity or direction. If irrelevant to the specific task/goal or does not fit into the model, note the information or potential connection but do not add to the model. Tell the participant throughout that you recorded the information so that it informs both the project and our other interpretations. Provide reminders that they can be honest because the information will be confidential

Q6b: Were there other values that we went over that you also think are important and want to include? [Repeat until participant is satisfied]

Q7: Are there other things that influence these variables? *[Example using traffic model]* Is there anything else you would like to add to your map?

Q8: When you look at the model you created, is there anything you think is missing, or that you want to add to better capture how you think about the food system in Flint?

Section 3: Leverage Points

The next thing we're going to do is to consider the leverage points, so what changes might improve the system. *[Example using traffic model]*

Q9: So now considering your map of the current Flint food system, how would you make changes to improve it?

- As a reminder: This could be by adding a new concept, adding a new connection, or changing a connection.

Section 4: COVID-19

This is the end of the main part of the modeling process, so I'm going to quickly save this file, then ask you a few questions related to COVID-19.

Q10: How would you describe the impact of COVID-19 on the map that you've made?

Probes:
- How would you draw connections between COVID and the different sectors?
- What is your understanding of how COVID is impacting the different values?

Q11: Is there anything else you would like to add or change about how you've represented COVID-19 and its impacts in your map?

Section 5: Wrap-Up

Q12: We've talked a lot about different food system sectors and values, and the impact of COVID-19. Is there anything important about this conversation that I forgot to ask you, or something that you want to add?

[Thank participant, provide evaluation survey, remind of informed consent, invite to reach out with any questions or concerns]

3.7.2 Appendix B: Definitions of Food System Values

Aggregate Food System Values:

- **Education:** Opportunities to learn food skills and apply them to career development.
- **Community Empowerment:** empower communities to support local economic developments that fosters a sense of community and prioritizes residents' cultural values.
- **Quality of Life is Respected:** Dignity, choices, comfort, and safety is respected for all residents throughout the food system.
- **Partnerships:** the food system should promote creativity and problem-solving to produce trust and strong partnerships that provide leadership and support collaboration and communication.
- **Nutritious Foods:** Offer more food options that are high in nutritional content, contain less additives and preservatives, and come in appropriate portions.
- **Affordability:** Food should be priced so that community members can access the type, quality, and quantity they require.
- **Availability:** The type, quality, and amount of food required for community members to conveniently feed their families and themselves should be physically present.

Original Food System Values from FLPP workshops:

Table B3-3: Value definitions from FLPP workshops (Belisle-Toler et al., 2020)

Values	Definition
Education	Educational opportunities teaching food production and preparation skills such as gardening, cooking, and canning in addition to opportunities for people to learn more about nutrition, health, and career development.
Community empowerment	Empower community members to strengthen and support local economic development that fosters a sense of community and prioritizes residents' cultural values.
Quality of life is respected	Respect an individual's quality of life through support of choice, dignity, comfort, and safety in the food system to enhance common good.
Partnerships	Trust and communication within the food system is essential to build effective collaboration across organizations, and bolster creativity, leadership, and problem-solving skills.
Nutritious foods	A diversity of nutritious foods that benefit health need to be available.
Affordable foods	Lower prices of food

Available foods	Culturally relevant food options are available either close to home or in stores that are easy to get to and meet needs, tastes and preferences, including prepared and local options.

3.7.3 Appendix C: Novel Components

Table C3-4: Components and number of mentions, ID refers to the numerical IDs used in Figure 3-22

ID:	Component Name	# of Mentions
1	Use of Retail	51
2	Grocery Stores	51
3	Convenience Stores	51
4	Farmers Markets	51
5	Local Restaurants	51
6	Chain Restaurants	51
7	Use of Supplemental Sector	51
8	Ability of Supplemental Sector	51
9	Ability of Emergency Sector	51
10	Use of Emergency Sector	51
11	Nutritious Foods	46
12	Education	42
13	Availability	39
14	Affordability	38
15	Access to Transportation	34
16	Quality of Life is Respected	30
17	Partnerships	30
18	Gardening + Local Agriculture	29
19	Community Empowerment	29
20	Income + Employment	17
21	Grocery Store Closures	15
22	Convenience	15
23	Funding + Grants	14
24	Food Waste	13
25	Accessibility	12
26	Healthy Food Choices	12
27	Choice	11
28	Flint Fresh + Food Hub	10
29	Building Community	10
30	Youth Engagement	10
31	Trust	9
32	Access to Land	9
33	Knowledge of Foods & Preparation	8
34	Availability of Cultural Foods	8
35	Freshness/Quality of Food	8
36	Health & Well-Being	7
37	Physical Health	7
38	Community Engagement	7

39	Flint Water Crisis	7
40	Food Access	7
41	Limited Operation Hours or Days	6
42	Seasonality	6
43	Conflict & Competition for Funding + Resources	6
44	Effective/Meaningful Community Engagement	6
45	School Meal Program	6
46	Food Choices Based on Time + Convenience	5
47	Crime	5
48	Local Food Businesses/Retail	5
49	Geographic Disparities/Differences	5
50	Non-Local Vendors + Resellers	5
51	Community Support Networks + Social Connections	5
52	Local Food Economy	5
53	Resilience	4
54	Loyal Customer Base	4
55	Sustainability	4
56	Delivered Food	4
57	Compassion/Sensitivity/Awareness/Intentionality of Organizations + Institutions	4
58	Social Inequities/Disparities	4
59	MSU Extension	4
60	Lack of Grocery Stores	4
61	Sense of Community, Cohesion, Stability, Safety	4
62	Prepared Foods in Market	4
63	Expectation of Free/Convenient Food	3
64	Unhelpful, Ineffective, Misguided, or Extractive Efforts	3
65	Mentality/Attitudes/Prioritization	3
66	Housing	3
67	Quality of Retail	3
68	Regulations	3
69	Consistency & Stability	3
70	Social Influences/Media	3
71	Feeling Unwelcome	3
72	Commercial/Community Kitchens	3
73	Marketing/Advertisements	3
74	Hurley Farmacy	3
75	Access to Resources	3
76	Racial Inequities	3
77	Stigma + Fear of Judgement	3
78	National Policy/Political System	3
79	Knowledge of How Food is Grown/Produced	3
80	Equity + Justice	3
81	Performance/Success in School or College	3

82	National/Global Agriculture	3
83	Youth Food Access	3
84	Food Costs (Sourcing)	3
85	Addiction	2
86	Ability/Space to Self Resolve/Become Self-Sufficient	2
87	Independence	2
88	Effective/Successful Efforts by Organizations	2
89	Accessibility of Emergency Food	2
90	Hunger	2
91	Safety	2
92	Power Structures/Differences	2
93	CRIM	2
94	Volunteers	2
95	Ease of Use	2
96	Limited Resources	2
97	Racism	2
98	Health Disparities + Disproportionate Health Burdens	2
99	Economic Disinvestment, Suppression, Decline	2
100	Agricultural Groups	2
101	Demand for Commercial/Community Kitchen Resources	2
102	Food Sovereignty	2
103	Closeness to/Knowledge + Understanding of Community	2
104	Policy Barriers, Issues, Limitations	2
105	Profits/Profit Margins	2
106	Access/Ability to Prepare Food	2
107	Sharing Resources	2
108	Silos + Lack of Coordination + Exclusion	2
109	Domination of/Disconnect Between Local Food & Large Companies	2
110	Safe Community Space	2
111	Food Gleaning/Rescue Programs	2
112	Accessibility of Education/Events	2
113	Language Barriers	2
114	Informal Food Sector	2
115	High Emphasis/Presence + Reliance on Emergency Sector	2
116	Community-Focused/Collaborative Efforts	2
117	"What's in it for me?"	2
118	Low Awareness/Knowledge of Programs	2
119	Difficulties Accessing Supplemental Nutrition Programs	2
120	Avoid Mistakes, Use Best Practices, Address Multiple Goals	2
121	Local/Community Based Organizations	2
122	Refrigeration	2
123	Excess of Food	2
124	Lack of Demand for Fresh Food	2

125	Financial Viability of Farming	2
126	Peer/Community Knowledge Sharing	2
127	Sourcing of Locally Produced Food	2
128	Self- Sufficiency/Sustaining	2
129	Economic + Employment Opportunities	2
130	Pride/Unwilling to Ask for Help	2
131	Produce/Unprepared Food in Market	2
132	Demand for Local Food	2
133	Support for Local Food	2
134	Composting	2
135	Purchase of Immediate Non-Essentials	1
136	Financial Planning/Skills	1
137	Mental Health	1
138	Case Management & Mental + Physical Health Care	1
139	Lack of Understanding of Needs & Trauma	1
140	Poverty	1
141	Confidence in Food	1
142	Growth Constraints	1
143	Lack of Space/Demand for Chain Stores	1
144	Farmers market move	1
145	Financial Viability of the Farmers Market	1
146	Stability of Food System	1
147	Chain Retail	1
148	Demand for Emergency Food from People Outside Flint	1
149	Vehicle Food Pick Ups	1
150	Limited Funding for Basic Needs	1
151	Top-Down Funding/Resources	1
152	Reliance on the Food Bank	1
153	Sodexo	1
154	Flint School Board	1
155	Operational Capacity of Producers	1
156	Environmental Pollution	1
157	Outsourcing in Education System	1
158	Food Safety	1
159	Sharing Food	1
160	Cultural Markets	1
161	Cultural Influences	1
162	Funding + Efforts by Institutions/Organizations	1
163	Grassroots/Community Leaders	1
164	Food system institutions	1
165	Lack of Opportunities	1
166	Other Historical Influences	1
167	Lack of Community Educators	1

168	Over Emphasis of Reducing Fraud	1
169	Ability of Supplemental Programs to Answer Questions	1
170	Layout of stores	1
171	Food Choices & Diet Disparities	1
172	Economic Inequities/Disparities	1
173	Dining / Eating Experience	1
174	Fragility of Resources/Operations	1
175	Social Determinants of Health	1
176	Seasonal Extension + Hoop Houses	1
177	Minimal Use of Established Hoop Houses	1
178	Power/Influence of Emergency Sector	1
179	Supplemental Nutrition Programs Electronic System	1
180	Age	1
181	Local Economic Development	1
182	Lack of Policies and Integration	1
183	Effective Educators	1
184	Emergency Sector Organizations + Institutions	1
185	Food Citizenship	1
186	Climate Change	1
187	GM Closure	1
188	Lack of Response from Government/Administration	1
189	Socioeconomic Influences	1
190	Lack of Rigor of Flint Schools	1
191	Feeling of Belonging	1
192	Racial Healing	1
193	Latinx Technology and Community Center	1
194	Distribution of Other Basic Needs	1
195	Edible Flint	1
196	Limitations to Supplemental Benefits	1
197	Effective Programing	1
198	Distribution of Resources to Whole Community	1
199	Flint Kids Cook Program	1
200	Flint Food Works	1
201	Start Up Costs	1
202	Licensing Requirements	1
203	School Food Staff	1
204	Flint Community Schools	1
205	Profit-Driven Retail	1
206	Public Awareness of Food System	1
207	Challenge to Build Trust	1
208	Additional Effort to Communicate and Collaborate	1
209	Retailers Signing Up to Supplemental Programs	1
210	Mobile Farm Stands	1

211	Qualifications + Cost to Access Food Bank	1
212	Technological Barriers	1
213	Left Over/Expired Food	1
214	Financial Viability of Emergency Food Organizations	1
215	State Level Agencies	1
216	Bureaucracy/Complex Internal Procedures	1
217	Small Grocery Stores	1
218	Limited Service Areas of Delivery Programs	1
219	Cooperative Production	1
220	Desperation + Feeling Powerless // Normalization of Current Conditions	1
221	Public Infrastructure	1
222	Lack of Funding for Public Projects	1
223	Youth Well-Being	1
224	Programs + Vouchers for Supplemental Nutrition Programs	1
225	Extra Resources to Process Locally Produced Food	1
226	Competition with Resellers	1
227	Lack of Understanding of Local Production from Local Restaurants	1
228	Access to Capital	1
229	Difficulties Sticking it out" in Local Agriculture"	1
230	CSA Boxes	1
231	Convenient Nutritious Foods	1
232	Skills/Knowledge Gap between Gardening and (for sale) Agriculture	1
233	Time Available to Participate in Education	1
234	Low Energy/Momentum for Change	1
235	Competition with Free Food	1
236	Greenhouse & Women’s Farm @ Ascension	1
237	Access to Water	1
238	Abuse	1
239	Healthcare Costs	1
240	School Gardens	1
241	Economic Resources	1
242	Mismatch between Funding & Training	1
243	High Labor Inputs	1
244	Perception that Local is More Expensive	1
245	Single Parent Households	1
246	Industrial Agriculture Lobbyists	1
247	Limited Funding for Supplemental Nutrition Programs	1
248	Few Chain Options	1
249	Geographic Pride / Identity	1
250	Non-Local Customers	1
251	Grocery Stores outside of Flint	1
252	YMCA	1
253	Mobile Feeding + After School Sites	1

254	Food Preparation Safety	1
255	Unavailable Parents	1
256	Oldest Sibling Responsible for Getting + Preparing Food	1
257	Community Mobilization	1
258	Grant Limitations	1
259	Financial Viability of Restaurants	1
260	Education on Financial Planning/Skills	1
261	Transportation Vouchers	1
262	Limited Parking	1
263	Transportation by Foot	1
264	Understanding of Resources + Respect for the Land	1
265	Lack of Mandate for Local Food	1
266	Understanding of Infrastructure	1
267	Soil Health	1
268	Feeling of Vulnerability (Social/Emotional Experience)	1
269	Disabilities/Other Challenges Acquiring and Transporting Food	1
270	Recycling	1
271	Integrity + Privacy	1
272	Supplemental Nutrition Programs Asking Too Many Questions	1
273	External Leadership	1
274	Lack of Signage/Information Differentiating Local Vendors	1
275	Understanding Value of Local Food	1
276	Importance of Shelf Stability to Choice	1
277	Availability of Supplemental Nutrition Programs in Stores	1
278	Supplemental Nutrition Programs Electronic System Crashing	1
279	Community Not Feeling Involved in Partnerships / In Control	1
280	GCCARD	1
281	Senior Nutrition Programs	1

3.7.4 Appendix D: Categorization Schemes & Definitions

Table D3-5: High-Level & In-Depth Categorization Scheme, with the number of components within each category and definitions.

In-Depth	**Category:**	**High-Level**
# of Comp.:	**Outcomes**	**# of Comp.:**
17	Equity & Justice	17
Includes social and economic equity and justice, as well as equitable access to things like opportunities, resources, or services.		
10	Food Security Outcomes	14
Physical and economic access to food that is safe, nutritious, and preferred. Includes aspects like food utilization, access, and availability.		
24	Systemic Outcomes	18
Outcomes of the food system like environmental security, food sovereignty and citizenship, or sustainability.		
24	Well-Being Outcomes	21
Includes social well-being (feeling/sense of community, quality of live is respected, trust, individual social functioning), physical and mental health, and community empowerment.		
# of Comp.:	**Drivers**	**# of Comp.:**
15	Socioeconomic Drivers	
Includes economic drivers (food prices, taxes), sociocultural drivers (culture, social norms, traditions, etc.), and governance and policy drivers.		
	Economics	29
	Economic aspects of or influences on the food system, like food price, subsidies, taxes, profit, etc.	
	Governance & Policies	11
	Formal and informal governance systems and mechanisms like regulations, policies, and programs.	
2	Environmental Drivers	
Climate change, seasonality, etc.		
13	Food Environment Drivers	

Influences on what/where people will eat like convenience, advertising, preferences, attitudes, beliefs, experience of shopping/eating, food quality and safety.		
6	Historical Events/Trends	
Events, shocks, or trends that have influenced the present system.		
# of Comp.:	**Barriers**	**# of Comp.:**
9	Attitudinal Barriers	
Barriers based on attitudes, values, beliefs. For example, prioritization, resistance to change, demand, or interest. May be influenced by social or cultural norms, pressures, or traditions.		
8	Governance/Regulatory Barriers	
Limitations placed by regulations or policies or related to governance processes.		
16	Interactional Barriers	
Barriers related to interactions among organizations and/or community members, includes issues like competition, conflict, power structures, and communication.		
9	Knowledge/Ability/Information Barriers	
Barriers based on a gap/lack of knowledge, ability, or information.		
7	Operational Barriers	
Barriers based on missing, negative, or ineffective practices/actions. Lowering these barriers would encompass a change to current decision-making, routines, or structures.		
13	Resource Barriers	
Barriers from or on resources such as funding, costs, time, labor, or other resources.		
16	Technological/Logistic/Capacity Barriers	
Limitations related to technological capabilities, capacity, or logistics.		
# of Comp.:	**Activities**	**# of Comp.:**
6	Production Activities	14
The growing of crops and rearing of animals either through agriculture at any level.		
1	Processing + Packaging Activities	
The washing, packing, and processing of plant and animal products.		

34	Distribution & Retail Activities	
	The distribution and/or sale of food through retail, emergency, supplemental, informal or exchange processes.	
	Retail Sector	37
	Establishments that sell food that needs to be prepared at home, or food ready for consumption.	
	Emergency Sector	16
	Sector that provides food at no cost, utilizing donations of food and money. Includes emergency sector organizations.	
	Supplemental Sector	18
	Concepts associated with the various supplemental nutrition programs.	
3	Consumption	13
	Consumption activities includes food choice, preparation, and eating.	
5	Disposal & Waste Management Activities	6
	Municipal waste, composting, or recycling of waste. Includes food gleaning/rescue programs.	
12	Cross-Sector Institutions	
	Organizations, groups, and institutions that interact with more than one food system sector.	
16	Interactions	
	Interactions among community members and/or groups and institutions, including engagement/collaboration, networking and self-organizing activities, and investment/funding.	
	Community	21
	Community communication and collaboration, as well as engagement between organizations and community members.	
	Organizations & Partnerships	23
	Organizations, groups, and institutions, as well are partnerships and collaborations among them.	
6	Flint Community Schools	
	Activities and institutions associated with Flint Community Schools, including staff, school board, school gardens, and school meal programs.	
4	Education & Knowledge	14

Opportunities to learn food skills (cooking, gardening, agriculture, nutrition, health, canning) and apply these to career development if desired.		
5	Built Environment/Infrastructure	9
Transportation, housing, community spaces, etc.		

3.7.5 Appendix E: Metamodel Evaluation Survey

3.7.5.1 Survey Development:

Three dimensions of the metamodels were evaluated by survey participants based on their understanding of the Flint food system: Components, themes, and scenario outcomes. Participants watched short videos (~ one minute) before each section that introduced the meaning of their choices and walked through the survey using an example transportation system.

Components: A random sample of twenty novel components with more than three mentions were used in the evaluation tool. Participants sorted components into three categories of "Important to Include," "Neutral," and "Not Important to Include." Then participants ranked the components they rated as "Important to Include" in order of importance.

Themes: The high-level categories most correlating to novel themes (i.e. excluding the four sectors and food security outcomes) were included and displayed as a color cognitive spectrum. As determining differences between and developing preferences for themes can be a cognitively challenging task, participants were asked to first determine their optimal percentages for the themes which could then be used as a decision heuristic for comparing the four metamodels. Participants "liked," "disliked," and left "neutral" the breakdowns of key themes for the four metamodels (Figure 3-20). Then they selected their preferred representation from the options they "liked."

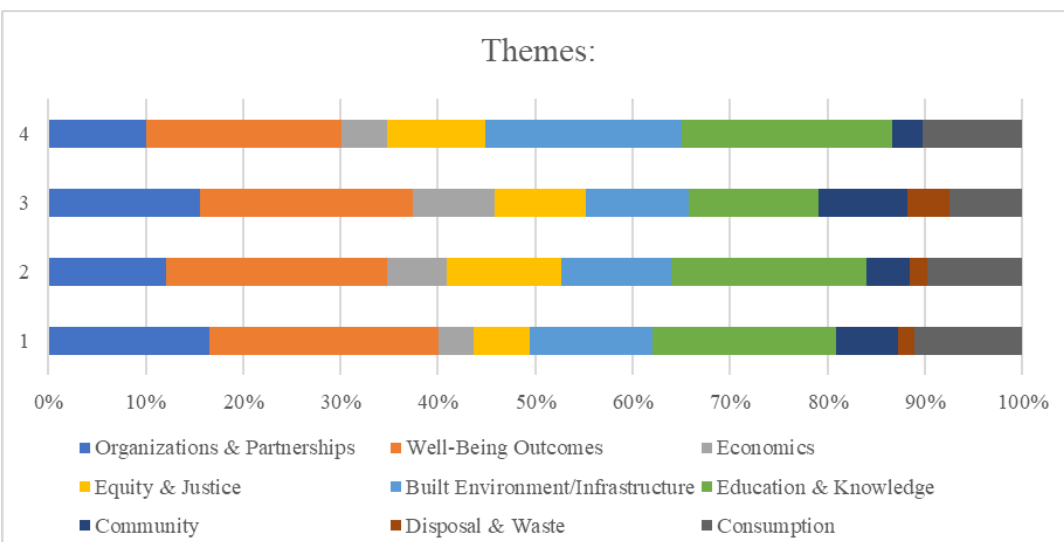


Figure E3-20: Color cognitive spectrum of key themes presented to survey participants

Scenarios: Three example scenarios were chosen that could be replicated across the four maps: 1) increasing use of convenience stores, 2) increasing access to transportation, and 3) increasing gardening and local agriculture. Four common components that were impacted in a specific scenario were selected as the evaluation metrics. Participants entered their predictions if the components would increase or decrease given each scenario (Figure 3-21).

3.7.5.2 Survey Results:

Components:

Table E3-6: Survey Results of Rating and Ranking Components. The most important components are ranked as one.

	1	2	3	4	5	6	7	8	9
Geographic Disparities/Differences	Neutral	8	7	14	7	8	6	Neutral	2
Accessibility	12	2	9	4	11	5	5	3	4
Local Food Economy	1	3	2	5	3	12	7	Neutral	9
Availability of Cultural Foods	7	Neutral	8	7	Neutral	Neutral	Not Imp.	Neutral	Neutral
School Meal Program	Neutral	12	Neutral	3	Neutral	9	4	Neutral	6
Choice	4	Neutral	6	8	Neutral	2	Neutral	Neutral	Neutral
Food Access	6	1	3	6	1	6	1	1	5
Community Support Networks + Social Connections	11	11	Neutral	2	10	Neutral	Not Imp.	7	Neutral
Sustainability	5	6	11	11	8	14	3	6	Neutral
Trust	2	Not Imp.	5	9	9	3	Not Imp.	Neutral	7
Social Inequities/Disparities	9	7	1	1	2	7	Not Imp.	Neutral	1
Freshness/Quality of Food	Neutral	4	4	12	4	1	2	2	3
Food Waste	10	Neutral	Neutral	15	Not Imp.	Neutral	Neutral	Neutral	Neutral
Community Engagement	Neutral	Neutral	Neutral	Neutral	6	10	Not Imp.	5	Neutral
Health & Well-Being	3	5	10	Neutral	5	4	Neutral	4	Neutral
Grocery Store Closures	Neutral	9	Not Imp.	13	Neutral	11	Not Imp.	Neutral	Neutral
Seasonality	8	10	Neutral	10	Neutral	15	Neutral	Neutral	8
Delivered Food	Neutral	Neutral	Neutral	16	Not Imp.	Neutral	Neutral	Neutral	Not Imp.
Funding + Grants	Neutral	Neutral	Not Imp.	Neutral	Neutral	13	Neutral	Neutral	Neutral
Conflict & Competition for Funding + Resources	Neutral	Not Imp.	Not Imp.	Not Imp.	Neutral	Neutral	Not Imp.	Not Imp.	Not Imp.

Themes:

Table E3-7: Theme preferences from survey participants

	Exp.: 9	Exp.: 5	C.D.: High-Level	C.D.: In-Depth	Most Preferred:
1	Like	Neutral	Like	Neutral	4
2	Neutral	Neutral	Neutral	Neutral	No opinion
3	Neutral	Like	Neutral	Neutral	3
4	Neutral	Dislike	Neutral	Like	1
5	Neutral	Neutral	Like	Like	No opinion
6	Like	Like	Like	Like	1
7	Neutral	Like	Neutral	Neutral	3
8	Dislike	Neutral	Like	Dislike	2
9	Like	Dislike	Neutral	Neutral	4

Scenarios:

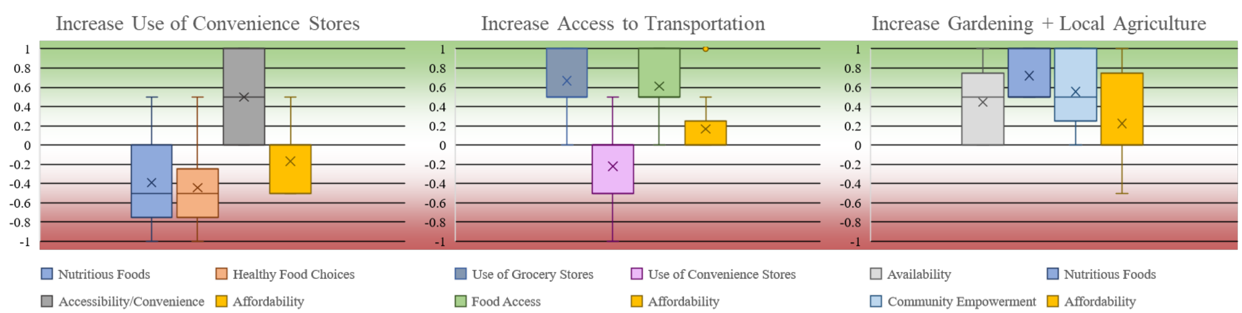


Figure E3-21: Distribution of scenario predictions from survey participants.

To compare the performance of the metamodels to the predicted scenario outcomes, we calculated the absolute difference between the scenario outcomes from the metamodels (Table 8, columns 4-7) and the average expected outcome from the survey results (Table 8, column 3). Then we took the sum across the scenarios to create a single value that could be used to compare the metamodels. See formula below.

Table E3-8: Scenario results from the four metamodels

Scenario:	Component:	Avg. of Survey	Exp.: 9	Exp.: 5	C.D.: In-Depth	C.D.: High-Level
Use of Convenience Stores	Nutritious Foods	-0.39	-0.51	-0.02	-0.65	-0.64
	Healthy Food Choices	-0.44	-0.25	-0.01	-0.36	-0.37
	Accessibility/Convenience	0.50	0.46	0.29	0.52	0.55
	Affordability	-0.17	-0.15	-0.12	-0.12	-0.13
Access to Transportation	Use of Grocery Stores	0.67	0.55	0.21	0.59	0.53
	Use of Convenience Stores	-0.22	-0.54	-0.56	-0.68	-0.63
	Food Access	0.61	0.18	0.33	0.51	0.42
	Affordability	0.17	0.36	0.23	0.26	0.16
Gardening + Local Agriculture	Availability	0.44	0.46	0.01	0.76	0.56
	Nutritious Foods	0.72	0.46	0.01	0.82	0.79
	Community Empowerment	0.56	0.46	0.01	0.56	0.47
	Affordability	0.22	-0.14	0.07	0.2	-0.05
	Total Abs. Difference:		2.17	4.04	1.58	1.70

Scenario performance formula:

$$s = \sum_{i=1}^{n} |O_i - P_i|$$

Where *O* is the observed scenario outcome, *P* is the predicted scenario outcome, and *n* is the number of components being tested within one scenario.

$$S = \sum_{k=1}^{N} s_k$$

Where *s* is the performance of the metamodel for one scenario and *N* is the total number of scenarios.

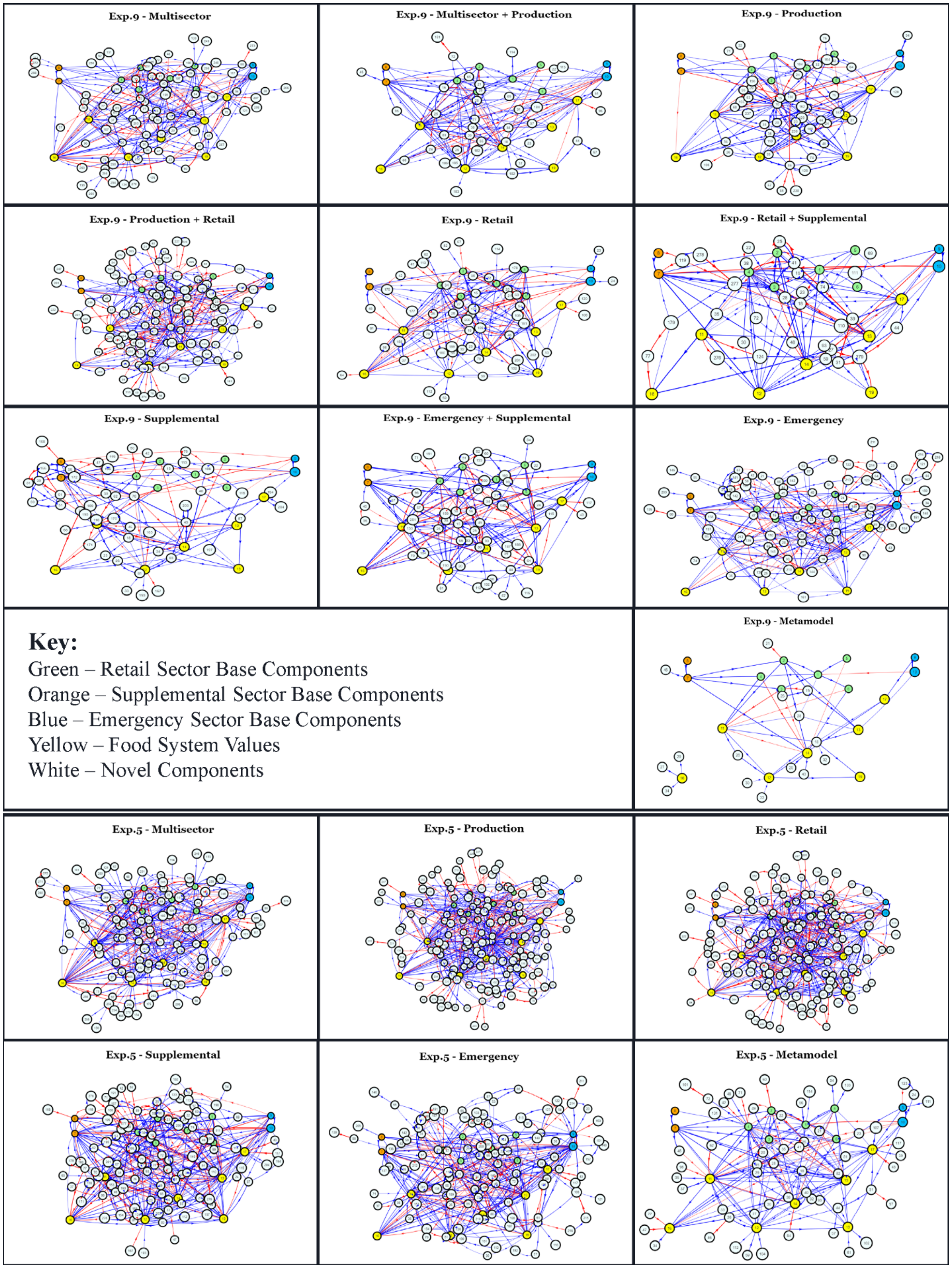
3.7.6 Appendix F: Group Membership

Table F3-9: Group membership of participants for each aggregation technique

ID:	Expertise: Nine Groups	Expertise: Five Groups		C.D.: In-Depth	C.D.: High-Level
5	Emergency + Supplemental Sector	Emergency Sector	Supplemental Sector	2	1
9	Emergency + Supplemental Sector	Emergency Sector	Supplemental Sector	3	3
19	Emergency + Supplemental Sector	Emergency Sector	Supplemental Sector	1	2
35	Emergency + Supplemental Sector	Emergency Sector	Supplemental Sector	5	5
51	Emergency + Supplemental Sector	Emergency Sector	Supplemental Sector	2	5
3	Emergency Sector	Emergency Sector		2	2
4	Emergency Sector	Emergency Sector		2	2
7	Emergency Sector	Emergency Sector		1	1
24	Emergency Sector	Emergency Sector		2	1
25	Emergency Sector	Emergency Sector		2	5
40	Emergency Sector	Emergency Sector		5	5
1	Emergency Sector	Emergency Sector		1	1
8	Multisector	Multisector		2	1
10	Multisector	Multisector		2	2
12	Multisector	Multisector		2	2
17	Multisector	Multisector		2	2
21	Multisector	Multisector		2	2
29	Multisector	Multisector		4	3
39	Multisector	Multisector		1	3
45	Multisector	Multisector		5	3
46	Multisector	Multisector		3	1
48	Multisector	Multisector		2	5
2	Multisector	Multisector		2	2
14	Multisector + Production	Multisector	Production	4	4
15	Multisector + Production	Multisector	Production	2	5
23	Multisector + Production	Multisector	Production	4	3

34	Multisector + Production	Multisector	Production	5	5
11	Production	Production		4	3
13	Production	Production		2	2
20	Production	Production		4	3
22	Production	Production		4	3
26	Production	Production		5	3
43	Production	Production		4	4
18	Production + Retail Sector	Production	Retail Sector	4	3
41	Production + Retail Sector	Production	Retail Sector	4	4
42	Production + Retail Sector	Production	Retail Sector	5	3
44	Production + Retail Sector	Production	Retail Sector	5	4
47	Production + Retail Sector	Production	Retail Sector	4	4
49	Production + Retail Sector	Production	Retail Sector	5	3
6	Retail + Supplemental Sector	Retail Sector	Supplemental Sector	2	2
31	Retail + Supplemental Sector	Retail Sector	Supplemental Sector	4	3
50	Retail + Supplemental Sector	Retail Sector	Supplemental Sector	5	3
16	Retail Sector	Retail Sector		2	2
28	Retail Sector	Retail Sector		1	1
30	Retail Sector	Retail Sector		2	2
32	Retail Sector	Retail Sector		2	2
33	Retail Sector	Retail Sector		5	1
37	Retail Sector	Retail Sector		3	3
27	Supplemental Sector	Supplemental Sector		1	5
36	Supplemental Sector	Supplemental Sector		5	5
38	Supplemental Sector	Supplemental Sector		3	5

3.7.7 Appendix G: Group Models


Exp.9 - Multisector
Exp.9 - Multisector + Production
Exp.9 - Production
Exp.9 - Production + Retail
Exp.9 - Retail
Exp.9 - Retail + Supplemental
Exp.9 - Supplemental
Exp.9 - Emergency + Supplemental
Exp.9 - Emergency
Key:
Green – Retail Sector Base Components
Orange – Supplemental Sector Base Components
Blue – Emergency Sector Base Components
Yellow – Food System Values
White – Novel Components
Exp.9 - Metamodel
Exp.5 - Multisector
Exp.5 - Production
Exp.5 - Retail
Exp.5 - Supplemental
Exp.5 - Emergency
Exp.5 - Metamodel

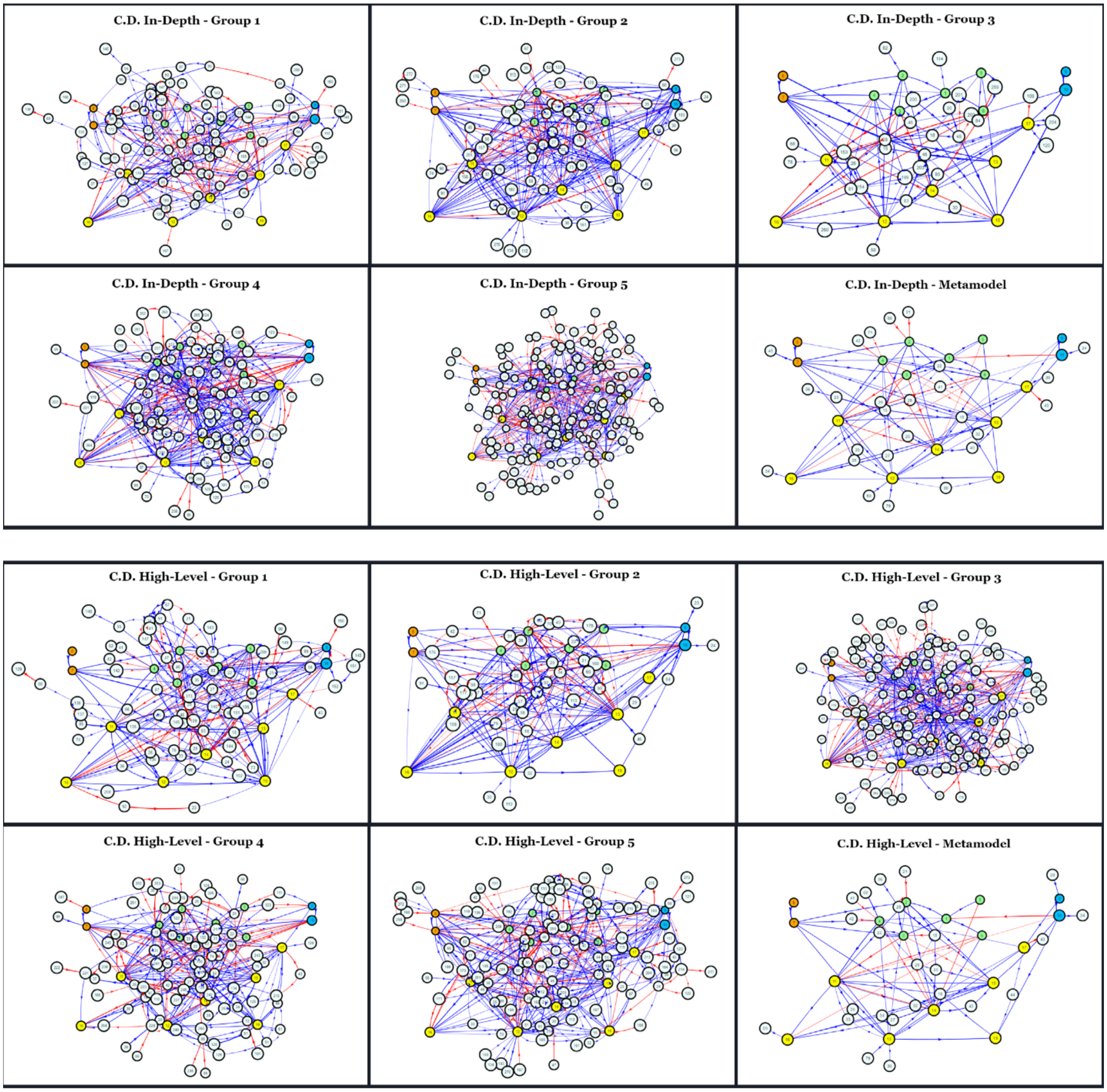


Figure G3-22: Group models and metamodels for each aggregation technique.

3.7.8 Appendix H: Dendrograms

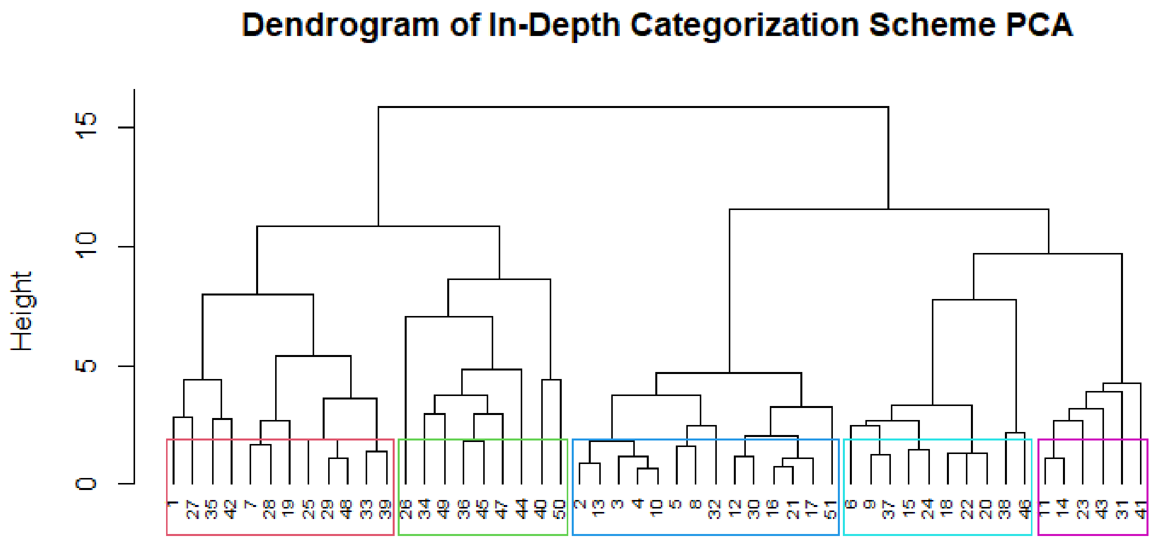


Figure H3-23: Dendrogram of Participants using the in-depth categorization scheme and PCA, split into five clusters.

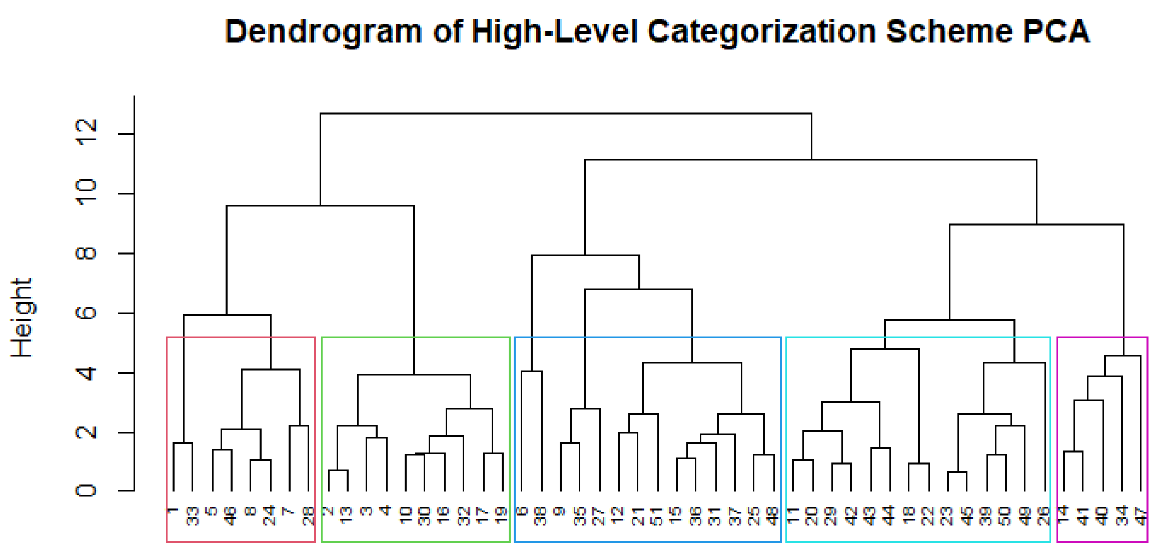


Figure H3-24: Dendrogram of Participants using the high-level categorization scheme and PCA, split into five clusters.

3.7.9 Appendix I: Micro-motifs

Table I3-10: Micro-motif real counts in the metamodels and individual maps, mean count from simulated random connected networks, and the probability of a network having a lower micro-motif count than the actual model.

		Metamodels				**Individual Maps**				***(Levy et al., 2018) Prevalence Results:***
		C.D.: In-Depth	*C.D.: High-Level*	*Exp.: Nine*	*Exp.: Five*	*Min.*	*Max.*	*Mean*	*St.Dev.*	
Multiple Causes	*Real Count:*	162	141	65	403	5	121	46.75	25.61	Very Common
	Avg. Sim. Count:	64.47	58.19	26.49	147.15	6.3	65.4	27.2	14.7	
	% Lower:	100%	100%	100%	100%	10.6%	100%	91.4%	19.1%	
Moderated Effect	*Real Count:*	26	34	13	88	0	30	9.96	7.45	Common
	Avg. Sim. Count:	5.89	5.48	2.47	7.91	0.32	6.13	3.19	1.47	
	% Lower:	100%	100%	100%	100%	0%	100%	87.9%	24.8%	
Multiple Effects	*Real Count:*	110	98	50	247	13	94	43.25	18.98	Balanced
	Avg. Sim. Count:	64.12	58.23	26.41	147.00	6.25	65.79	27.16	14.70	
	% Lower:	100%	100%	100.0%	100%	20.7%	100%	92.1%	18.1%	
Indirect Effect	*Real Count:*	157	136	68	468	12	163	62.04	35.08	Rare
	Avg. Sim. Count:	166.63	151.56	68.38	381.28	15.82	171.15	70.22	38.42	
	% Lower:	20.2%	9.1%	45.1%	100%	0%	96.9%	31.2%	34.1%	
Bidirectionality	*Real Count:*	4	3	0	9	0	5	1.29	1.49	Rare
	Avg. Sim. Count:	2.64	2.64	1.67	3.05	0.54	3.18	1.93	0.58	
	% Lower:	72.4%	52.3%	0%	99.6%	0%	99.3%	25.2%	31.1%	
Feedback Loops	*Real Count:*	0	0	0	10	0	7	0.94	1.61	Very Rare
	Avg. Sim. Count:	3.08	2.90	1.26	4.26	0.14	3.33	1.67	0.81	
	% Lower:	0%	0%	0%	99.2%	0%	99.9%	17.9%	30.5%	

3.7.10 Appendix J: Intragroup and Intergroup Cognitive Distances

Table J3-11: Intragroup and inter group cognitive distance for the groups that participants have been grouped based on their cognitive diversity.

C.D.: In-Depth				C.D.: High-Level			
Groups	Group Size	Intra-Group/Inter group distance	Average	Groups	Group Size	Intra-Group/Inter group distance	Average
Group 1	8	Intra-Group	7.61	Group 1	6	Intra-Group	6.23
		Inter-Group	9.10			Inter-Group	9.11
Group 2	13	Intra-Group	2.90	Group 2	19	Intra-Group	3.77
		Inter-Group	9.48			Inter-Group	9.90
Group 3	15	Intra-Group	6.58	Group 3	4	Intra-Group	7.85
		Inter-Group	9.24			Inter-Group	9.08
Group 4	5	Intra-Group	6.89	Group 4	11	Intra-Group	6.34
		Inter-Group	9.10			Inter-Group	9.20
Group 5	10	Intra-Group	12.41	Group 5	11	Intra-Group	6.85
		Inter-Group	8.96			Inter-Group	9.18

Table J3-12: Intragroup and inter group cognitive distance for the groups that participants have been grouped based on their expertise group.

Exp.: Nine Groups				Exp.: Five Groups			
Groups	Group Size	Intra-Group/Inter group distance	Average	Groups	Group Size	Intra-Group/Inter group distance	Average
All	11	Intra-Group	7.47	Emergency	12	Intra-Group	9.39
		Inter-Group	9.15			Inter-Group	9.06
All + Production	4	Intra-Group	3.48	Multisector	15	Intra-Group	6.25
		Inter-Group	9.10			Inter-Group	9.33
Emergency	7	Intra-Group	10.37	Production	12	Intra-Group	9.46
		Inter-Group	9.06			Inter-Group	9.06
Emergency + Supplemental	5	Intra-Group	9.67	Retail	15	Intra-Group	9.59
		Inter-Group	9.07			Inter-Group	9.03
Production	6	Intra-Group	4.75	Supplemental	11	Intra-Group	13.55
		Inter-Group	9.13			Inter-Group	8.88
Production + Retail	6	Intra-Group	6.99				
		Inter-Group	9.10				
Retail	6	Intra-Group	2.45				

		Inter-Group	9.16	
Retail + Supplemental	3	Intra-Group	10.93	
		Inter-Group	9.07	
Supplemental	3	Intra-Group	38.26	
		Inter-Group	9.01	

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Chapter 4 Utilizing Participatory Modeling and Leverage Points Perspective to Evaluate Interventions: A Case Study of the Flint, Michigan Food System

4.1 Abstract

Decades of research have documented racial and ethnic disparities that impede access to affordable and nutritious food. In this study, we adopt a mixed methods "solution oriented" approach to improve understanding of racial inequities in low-income urban food systems and evaluate interventions at a systemic level. We propose a method for synthesizing interventions grounded in a leverage points perspective and causal mapping. We elicited ideas for leverage points from 24 local food system experts in Flint, Michigan. By mapping the concepts and causal relationships described by participants in 84 different leverage points, we were able to aggregate ideas at different levels of specificity and quantitatively compare emergent themes. We found six themes for interventions: strengthening the local food system, expanding educational opportunities, increasing food access and healthy consumption behaviors, improving partnerships and engagement with community, shifting investment to better achieve food system goals, and reforming how governance structures operate. Lastly, we used a system archetype framing to analyze narrative data and identify structural areas for intervention. We found two prominent system archetypes driving undesirable food system outcomes - "Success to the Successful" and "Shifting the Burden." Based on the leverage points analysis grounded in systems thinking and aggregated local knowledge, we recommend developing a resilient and equitable local food system through both 1) provisioning resources, particularly to Black, Indigenous, and people of color (BIPOC) business owners and entrepreneurs, and 2) addressing

racialized barriers such as affordability and accessibility for community members to participate in the localized food system.

4.2 Introduction

4.2.1 Racial Equity & the US Food System

Equitable food systems are a foundational aspect of social and environmental justice. The United States food system has a deep history of discrimination and exploitation of marginalized groups and perpetuates racial and ethnic inequalities through outcomes like food insecurity, health disparities, and the loss of food sovereignty (Horst & Marion, 2019; Knox & Miller, 2022). Food insecurity disproportionately affects people of color through racial disparities for affordability (income and wealth, high food prices, etc.) as well as non-economic factors like limited food access, racial discrimination, and stricter regulations to food assistance programs (Anderson, 2008; Bowen et al., 2021; Cachelin et al., 2019). Regarding food access, supermarkets are largely located in suburbs due to city planning, private sector investment, and federal subsidies; in many urban areas there is lower accessibility of fresh produce and the food that is available in underserved areas through convenience/corner stores is more likely to be heavily processed, high calorie, and nutrient-poor (Block et al., 2004; Elmes, 2018; NYLS, 2012; Shaver et al., 2018). Members of these communities are more vulnerable to diet-related diseases and health outcomes such as obesity, heart disease, or hypertension (Drewnowski & Specter, 2004; Usher, 2015). Food is also a deeply personal and sociocultural experience, and another source of inequity stems from limited access to cultural foods and loss of traditional foodways (Anderson & Cook, 1999; Cachelin et al., 2019).

The breadth and depth of impact of food systems on racial equity highlights both the urgency and opportunity of food system interventions to address justice and sustainability. In the sustainability field, scholars have called for a shift away from "problem-oriented" towards "solution-oriented" research that links understanding of problematic dynamics to action and impact (Miller et al., 2014; von Wehrden et al., 2019). These efforts are often inter-/transdisciplinary, with emphasis on partnerships, collaboration, and community engagement (Kueffer et al., 2012; Robinson, 2008). Systems approaches and modeling are also common, which can serve as a useful tool for studying the interacting socio-environmental systems and to identify and evaluate fundamental solutions that are at an appropriate spatial and temporal scale to promote sustainable transformation (Kopainsky et al., 2018; Ruben et al., 2019). Participatory modeling processes harness the implicit and explicit knowledge of stakeholders to generate representations of socio-environmental systems (Voinov et al., 2018). There are many approaches to participatory modeling that range from quantitative methods like system dynamics modeling or agent-based modeling, to qualitative methods like cognitive mapping and causal loop diagrams. Causal mapping, which in its simplest form is graphical causal relationships between elements of a system, has been used for decades to model socio-environmental systems (Adebiyi & Olabisi, 2022; Gray et al., 2015; Kosko, 1986; Nabong et al., 2022; Schwermer et al., 2021). Causal relationships form the basis of common modeling methods like cognitive maps, mental models, and causal loop diagrams (Doyle & Ford, 1998; Voinov et al., 2018).

Through a case study of the Flint, MI food system, we elicited leverage points during semi-structured interviews with local experts and created causal representations of interventions. Modeling interventions in this way enable quantitative comparison of leverage points and the ability to aggregate local knowledge and community member preferences. Leverage points are areas of system intervention where a relatively small effort can yield a significant shift in the trajectory of the system (Meadows 2008). Utilizing the collective intelligence of experts through the aggregation of local knowledge and perspectives can be vital to capturing a holistic and accurate understanding of complex systems, and embed community values and preferences into decision making processes (Aminpour et al., 2021; Gray et al., 2015; Nadkarni & Nah, 2003). Finally, we will analyze system archetypes within the narrative data from the semi-structured interviews to evaluate the effectiveness of the proposed interventions. Ultimately, the key goal is to develop insights and recommend a set of interventions that achieves a community-defined desirable food system future in line with justice, sustainability, and food sovereignty.

4.2.2 Leverage Points Perspective

Donella Meadows introduced a list of twelve leverage points, places in a system where an action can create a proportionately larger change, in order of effectiveness (Meadows, 1999). Later, these twelve leverage points were synthesized by Abson et al. (2017) into four system characteristics: parameters, feedbacks, design, and intent (see Table 4-1). These four system characteristics are separated into “shallow” and “deep” leverage points, based on how effectively interventions would create system wide change (Abson et al., 2017). Grounded in this hierarchy of interventions, the “leverage points perspective” has emerged as an epistemological view of systems with the goal of transformative change (Riechers et al., 2022). It has been used in a variety of socio-environmental systems to, for example, identify, categorize, and evaluate leverage points (Burgos-Ayala et al., 2020; Fischer et al., 2022; Riechers et al., 2021; Rosengren et al., 2020). Beyond providing a framework to identify places to intervene in systems, the leverage points perspective can be a way to combine or transcend paradigms in sustainability science by linking current, causal relationships to a desirable future through interventions (Riechers et al., 2022; West et al., 2020).

Table 4-1: Leverage points and system characteristics, in order of effectiveness. Adapted from Abson et al., 2017

	Meadows (1999)	**Abson (2017)**
Shallow LPs	12: Parameters such as subsidies, taxes, and standards	**Parameters:** The relatively mechanistic characteristics typically targeted by policy makers
	11: The size of buffer stocks, relative to their flows	
	10: The structure of material stocks and flows	
	9: The length of delays, relative to the rate of system change	**Feedbacks:** The interactions between elements within a system of interest that drive internal dynamics
	8: The strength of negative feedback loops	
	7: The gain around driving positive feedback loops	
Deep LPs	6: The structure of information flows (access to information)	**Design:** The social structures and institutions that manage feedbacks and parameters
	5: The rules of the system (such as incentives and constraints)	
	4: The power to add, change, or self-organize system structure	
	3: The goals of the system	**Intent:** The underpinning values, goals, and world views of actors that shape the emergent direction to which a system is oriented
	2: The mindset/paradigm out of which the system arises	
	1: The power to transcend paradigms	

Some key strengths of utilizing a leverage points perspective are 1) accounting for and managing the complexity of socio-environmental systems, 2) combining causal and teleological reasoning, and 3) explicitly evaluating "deep" interventions that target transformative change (Abson et al., 2017; Fischer & Riechers, 2019; Rosengren et al., 2020). In addition, leverage points can also be evaluated in combination to maximize synergies and minimize unwanted outcomes/trade-offs (Kellner, 2023). In this case study, we use a leverage points perspective to guide our elicitation and evaluation of proposed interventions in the Flint, MI food system. We will study leverage points in line with recommended methodologies, primarily systems approaches and transdisciplinary research methods that promote the co-production of knowledge (Leventon et al., 2021).

4.2.3 Case Study: The Flint, Michigan Food System

Flint was once a prosperous city, but economic disenfranchisement and plant closures, and structural racism led to depopulation and an increase in the poverty rate (Highsmith, 2015). These trends can be tied to several causes, including redlining (a process of segregating Black families through discrimination in access to housing loans and insurance) beginning in the '30s, construction of the I-475 highway in the '70s which divided the community geographically, and the 2008 recession (Wentworth & Hodbod, 2020). A major influence on the industrial collapse was the departure of the automotive industry. The closure of General Motors (GM) plants in 1980's, 1999 and 2010, which at its peak in the late '70s employed 80,000 of 190,000 residents in Flint, catalyzed decades of economic decline (Wentworth & Hodbod, 2020). These factors have heavily influenced food security in the city and other food system outcomes.

The Flint Water Crisis, which began in April of 2014 when the city's water source was changed to the Flint River, furthered existing issues and deepened health inequities. The water source was switched to Lake Huron in late 2015 and a majority of the lead service pipes have been replaced over the last nine years; however, the physical and emotional effects of the water crisis persist (Diaz, 2022). One food system outcome of the Flint Water Crisis was sweeping public health programs that promoted the consumption of lead-mitigating foods. In addition, there was an influx of philanthropic funding for emergency food distributions and governmental changes to increase the use of supplemental nutrition programs.

These historical trends are steeped in structural racism, which influences how decisions get made, responses to shocks, and allocation of resources (Clark, 2019). Flint is a predominantly Black city and there have been clear racial inequities in how residents of Flint have experienced both urban decline and efforts to rebuild. Structural racism has been and continues to be a fundamental force behind the deliberate economic disenfranchisement of BIPOC Flint residents. For example, the location of supermarkets reinforces racial bias, as major grocery chains within the city of Flint have mostly closed (Shaver et al., 2018). Small retail outlets like convenience stores, party stores, and gas stations make up over half of the food outlets in Flint and the surrounding townships (Taylor et al., 2022). Convenience stores have become a primary source of food for some residents, which limits access to healthy, fresh, and affordable foods, especially for residents that rely on public transportation. Flint residents may need to travel outside of the city to visit a supermarket, which further entrenches racial and socioeconomic barriers to food access. The concept of "food deserts" has been prevalent in food systems literature, but scholars and activists have proposed a shift towards the term "food apartheid" which explicitly acknowledges the racial, geographical, and economic aspects of food access inequities as outcomes of systems that were constructed and not naturally occurring (Brones, 2018).

In sum, the Flint food system is in a state of food apartheid as there is deeply inequitable access to food. There are spatial inequities, differences in quality, availability, and nutrition depending on location and transportation options. There are also social inequities, as the lack of retail options, limited selection of emergency food distributions, and strict requirements for supplemental nutrition programs limits residents' ability to make their own choices about food, particularly for cultural foods and dietary options. Finally, the most visible economic inequity is affordability and the consistent mismatch between income and food price. Retail stores in Flint have higher food prices than the surrounding suburban areas (Mayfield et al., 2020) and in areas without easy access to grocery stores, residents are spending more on food, transportation, and/or time to shop (Sadler et al., 2013).

4.2.3.1 Flint Leverage Points Project:

The Flint Leverage Points Project (FLPP) was a community-engaged research project aimed at furthering understanding of the Flint food system and identifying leverage points for positive change. The project began in 2018 after being sparked by Flint's food system navigator identifying a need for more collaboration and research across the food system. FLPP was a collaboration between the Community Foundation of Greater Flint (CFGF) and Michigan State University (MSU). In addition, the project worked closely with a Community Consultative Panel (CCP) that advised the research team and had equitable input in the project (Olabisi et al., 2022). CCP members represented different sectors, including governance, production, faith-based and non-profit emergency food providers, and philanthropic organizations. There were three main research teams within FLPP: 1) Governance and Resilience, 2) Mental Modeling, and 3) System Dynamics. An evaluation team worked concurrently with the aforementioned teams to determine the extent to which they are meeting stated goals and objectives, and provided recommendations to improve the chances the project will meet said goals.

Throughout the project, community-defined food system values served as guidelines for food sovereignty in Flint (Belisle-Toler et al., 2021). Coined by Via Campesina in 1996, food sovereignty encompasses the rights of people to self-determination over their food system, including processes like production and distribution, as well as agricultural and food policy (Whyte, 2017). One key goal of FLPP was to center community voices, encourage participatory and engaged work, and ensure transparency and accountability throughout the research process. The duplicitous and harmful behavior of state and local government in the Flint Water Crisis has damaged residents' trust in governance and authority (Pauli, 2019). Similarly, a historical pattern of extractive research and unethical practices towards communities of color has created mistrust with academic research and unwillingness to participate (Brandon et al., 2005). The mistrust of academia and top-down decision-making highlights the importance of work that is grounded in equity. Through a literature review, semi-structured interviews with food system experts, and analysis of potential leverage points, we aim to 1) deepen understandings of how racial inequity impacts the Flint, MI food system, 2) evaluate interventions using a leverage points perspective, and 3) recommend actions to operationalize racial equity that are grounded in local knowledge and system understanding.

4.3 Methods

Using a mixed methods approach, we 1) established a general understanding of racial inequity in the food system through a literature review, 2) contextualized that information in the Flint, MI localized food system, 3) elicited food system experts' ideas for leverage points, and 4) synthesized and evaluated leverage points through causal mapping and analyzing system archetypes. The following sections cover each step of this process (Figure 4-1)

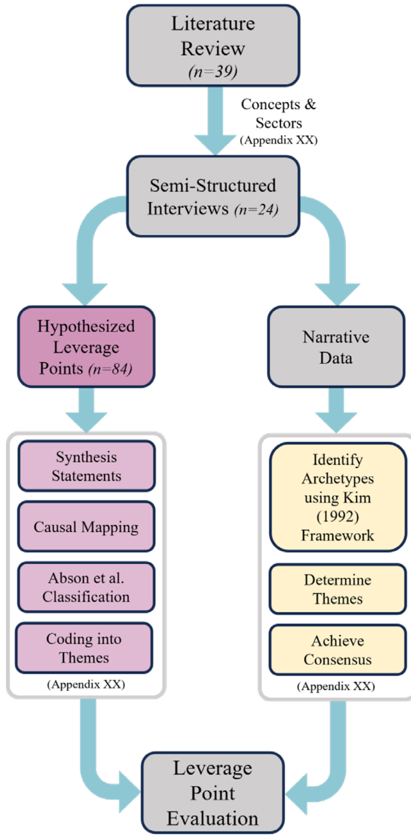


Figure 4-1: Visualization of methods from literature review, to semi-structured modeling interview, and synthesis and evaluation of leverage points.

4.3.1 Literature Review

An informal literature review was conducted on how racial inequity impacts the food system and how racial equity work is operationalized. Prominent databases like JSTOR, ProQuest, and SAGE Journals Online were searched using the keywords of "racial equity" and "food systems." Reference lists on the topic were also consulted, and gray literature such as policy briefs, technical reports, and online articles were also included in the search. Topically relevant academic articles were selected by researchers for inclusion, with priority given to documents that were included in multiple reference lists, present in searches across databases, and those that were more highly cited. The literature review is not intended to be a holistic and/or representative review of racial equity in food systems literature, but rather the theoretical and practical foundation upon which the Fuzzy Cognitive Mapping (FCM) interviews were based. Based on the final selection of documents, researchers developed an emergent coding scheme of key concepts. Then, two researchers qualitatively coded each document whether it included the concepts.

4.3.2 Semi-Structured Modeling Interviews

Leverage point elicitation occurred at the end of semi-structured virtual modeling interviews with local food system experts. Specifically, we used FCM, which is a semi-quantitative form of cognitive mapping. Participants were guided through conversations describing how racial inequity impacts the Flint food system with facilitators who created the map in the free software MentalModeler while screensharing and confirming that the structure was accurate. The interviews focused on racialized barriers to participating in five sectors of the local food system (production, processing and packaging, wholesale and resale, retail, and waste) which were identified in the literature review and validated in discussion with community partners (see Appendix A).

Participants (n=24) were elicited through snowball sampling, beginning with CCP members and other food systems experts with knowledge or experience about racial equity. In a post-interview survey, each participant was asked to recommend up to three additional experts who could speak to one or many of the local food system sectors in Flint. The interview process was adapted from the previous set of FCM interviews (see Knox et al., 2023). First, participants connected each food system sector, then added "Racial Inequity." Next, participants were asked to add any additional concepts that they thought were important to the model and asked if they wanted to discuss the major shocks of the Flint Water Crisis and/or COVID-19. Lastly, participants were asked to examine their map and share ideas they had for leverage points or changes they would make in order to improve the Flint food system. Future work will detail findings from the FCM maps, as well as how FCM and "what-if" scenarios can be used to evaluate leverage points. However, this paper explores a more general method for collecting and synthesizing leverage points from narrative data. See Appendix A for a detailed description of data collection and preparation.

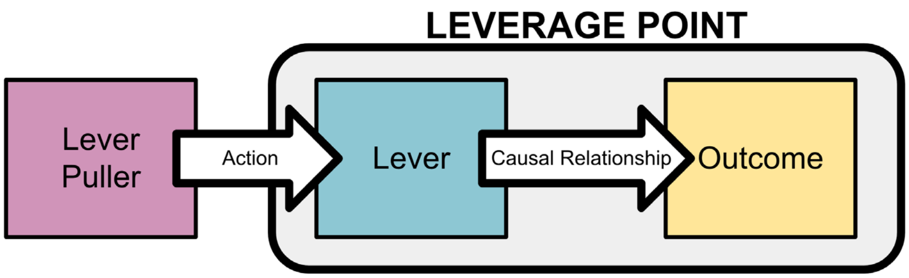


Figure 4-2: Visual of the leverage point model used to sort theorized leverage points.

To quantitatively analyze leverage points, researchers distilled each idea for an intervention into a one- to two-sentence synthesis statement (Fischer et al., 2022). Translating text or narrative data into concepts and relationships is a well-established practice in several disciplines, with methodologies and analyses that vary depending on research purpose (Eden et al., 1992). For example, management sciences use techniques like Interpretive Structural Modelling (ISM) to identify factors and relationships to structure issues within systems (Attri et al., 2013). Operations research (OR) also uses problem structuring methods (PSMs) like Strategic Options Development and Analysis (SODA) to develop causal maps of complex topics with groups or individuals (Ackermann & Eden, 2010). This study utilized a qualitative approach where researchers determined concepts and causal relationships, including direction and polarity, from each synthesis statement using our leverage points model based on work by Meadows (1999) and Chan et al. (2020), see Figure 4-2. The causal relationships have direction, i.e. an arrow pointing from concept A to concept B shows that A causally impacts B, and polarity. For the purposes of this paper, a positive causal relationship, where an increase or decrease in A connotes the same direction of change in B, will be shown through blue connections, while a negative causal relationship, where change occurs in opposite directions, will be shown through orange connections.

This methodology was selected to address the major challenge of working with this kind of qualitative narrative data: high variation in participants' answers about potential leverage points. This can be shown through two examples of synthesis statements about leverage points related to governance. One is more specific, recommending to "centralize the approach to urban planning (for example changing state land use law around development) to eliminate the effects of segregation," while another is vaguer by suggesting to "change administration and implementation of biased policies, to better serve all populations in the community and promote equity." Both leverage points advocate for using government and policy to achieve equity goals, but the first can be interpreted into an intervention with far fewer assumptions about specific policies or areas to target. Consider the example in Figure 4-3 with no causal relationships; the participant wants more support for local entrepreneurship, but researchers would need to infer *what* that support would be and/or *how* supporting local businesses would result in positive change. One option would be to exclude hypothesized leverage points that lack causal relationships between actions and outcomes, but then that data is lost. Thus, we choose to preserve support for different levers or emphasis on important outcomes by including answers without causal relationships. Once all statements were mapped into causal relationships, the frequency of mention was used to determine the size of concepts and weights of connections, for the purpose of easily visualizing common pathways for positive change.

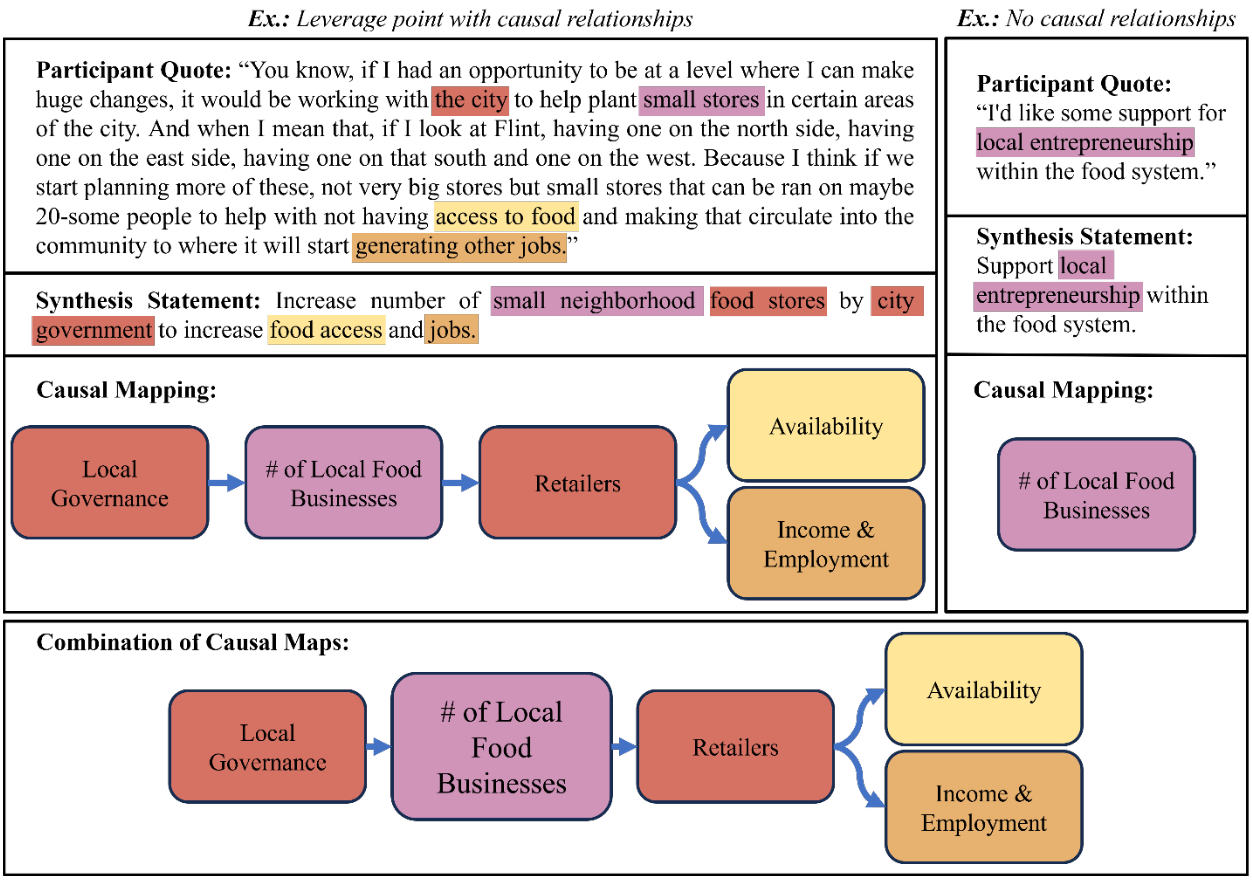


Figure 4-3: Examples of causal mapping process from participant statement to synthesis statement to causal mapping, to combination of different causal maps.

Finally, the leverage points were qualitatively grouped into emergent themes based on an inductive coding scheme (see Table 4-2), as well as being classified into the four characteristics of leverage points identified by Abson (2017) (Riechers et al., 2021). Each intervention could be coded into multiple themes, but only one characteristic.

Table 4-2: Leverage points themes, with theme and definition.

Theme:	Definition:
Local Food Economy	Strengthen the local food economy by expanding current locally owned food businesses or creating new ones and increasing community support for local food.
Knowledge	Reform food system education to better inform people and offer educational opportunities around nutrition, health, and food system skills.
Food Access & Consumption	Positively impact food access and shift consumption behaviors towards improved diets, food choices, and overall health.
Engagement	Improve partnerships and engagement between and among food system organizations, community members, and other groups to better achieve community values.
Investment	Change how funds and investments are allocated within the food system, through shifting funding from one place to another, expanding current funding, or creating new funding streams.
Governance	Reform and utilize governance structures to achieve food system goals.

4.3.3 Archetypes

Archetypes are system structures that produce characteristic patterns of behavior. System archetypes are a well-documented tool for communicating the structure and behavior of systems and have been applied across various contexts (Kim & Anderson, 1998; Senge, 2006). They are useful both as a communication heuristic and as an initial step towards building a model that reflects a system of interest. Kim and Anderson (1998) describe system archetypes as recurring narratives or stories that help build an understanding of system structure by being attuned to systems' behavior over time. Like many in the field of system dynamics (Newell, 2012; Senge, 2006; Wolstenholme, 2004), Kim and Anderson (1998) find that archetypal structures promote systems thinking by creating a communicative environment to express intuitive observations of familiar systems. In this study, we used system archetypes to diagnose patterns in the FCM data that produce undesirable system behavior.

All the narratives from 24 semi-structured interviews were analyzed by two researchers independently, in two distinct phases, to extract archetypes and themes from the narratives. The initial phase was a deductive analysis, wherein we employed Kim's (1992) comprehensive framework, which details eight specific system archetypes. This framework acted as a critical guide in identifying relevant archetypes within the narratives, with a specific focus on those associated with racial inequality in the food system. Through this analytical lens, we successfully identified two predominant system archetypes.

In the subsequent phase, we moved to an inductive analysis, examining the narratives related to each identified archetype. This phase was crucial for identifying and categorizing the underlying themes within each archetype. Our analysis of the first archetype uncovered three distinct themes, each offering unique insights into the archetype's undesirable dynamics. In contrast, the analysis of the second archetype revealed a single, yet impactful theme. Following this analysis, we engaged in in-depth discussions to compare and reconcile the identified system archetypes and their corresponding themes. These collaborative discussions were key in resolving interpretative differences and achieving a unified consensus on our findings. This analytical approach significantly enhanced our grasp of the intricate relationship between racial inequity and the existing undesirable dynamics in the food system.

4.4 Results & Discussion

4.4.1 Literature Review

Based on the database and reference list searches, 39 documents were reviewed. Researchers identified 43 key concepts within the documents that related to racial equity and the food system, and 127 ways in which racial equity is operationalized in food systems work (see Appendix B for list of documents and concepts). In each document, researchers identified instances where key concepts were acknowledged by authors, either explicitly or implicitly. The most frequently acknowledged concepts include structural racism/inequity (n=21), government policies, programs, and subsidies (n=17), relationships between actors (n=15), financial capital (n=13), racial equity/inequity (n=13), health and well-being (n=12), acknowledgement and awareness (n=10), justice (n=10), and place-based strategies (n=10). The concepts from the literature review were used to scope the FCM interviews.

4.4.2 Deep vs Shallow Leverage Points

Participants described 84 different ideas for positive change, of which 13 lacked a causal relationship. The remaining 71 were mapped into causal diagrams and coded based on the six emergent themes and Abson's four characteristics of leverage points (see Appendix C). Overall, the 84 hypothesized leverage points broke down into 27 leverage points targeting *parameters*, 41 targeting *feedbacks*, 12 targeting *design*, and four addressing *intent* (Figure 4-4). We found a high number of shallow leverage points, either parameters or feedbacks, and fewer deep leverage points. This result is relatively unsurprising. Shallow leverage points are more commonly discussed and implemented interventions. We had many interventions classified as "feedbacks" as they would generally increase the power of feedback loops or shorten delays. We theorize that this could be partially due to the tremendous influx of philanthropic funding towards the Flint food system, which has supported many local organizations and programming. With more resources, partnerships, community support, and reach, these entities could then hypothetically create positive change at a broader level.

While many of the hypothesized leverage points target feedbacks, and thus are structurally less impactful to the entire system, we do not want to diminish the potential these interventions have for positive outcomes. Would a locally owned and operated food cooperative transform the Flint food system? Probably not, and likely not as much as equity centered federal policy that would be categorized as "design." However, for the neighborhood a co-op was situated in, and the people employed by the business, it could be transformative. This is why we recommend pursuing a portfolio of interventions. The food system is complex, and each sector and actor can contribute towards equity and food sovereignty. "Local Food Economy" was the most common emergent theme (n=35), followed by "Food Access & Consumption" (n=25), "Engagement" (n=24), and "Knowledge" (n=22). The two least common themes were "Investment" (n=13) and "Governance" (n=13). Surprisingly, no hypothesized leverage point discussed food waste or waste management. Themes like "Engagement," "Governance," and "Investment" contained more deep leverage points, as leverage points that discussed changing the foundational values of organizations or governance structures, or redistributing control over system, usually fell into those themes.

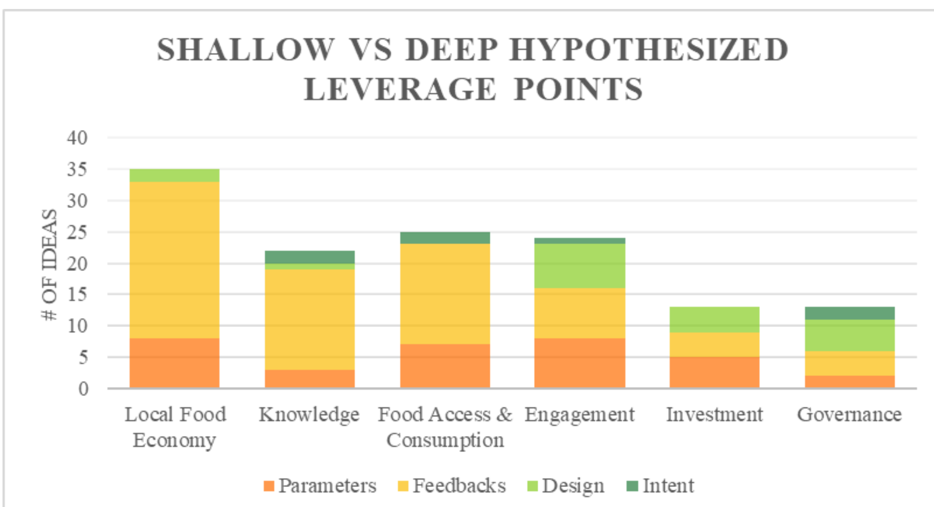


Figure 4-4: Results of coding leverage points into parameters, feedbacks, design, and intent within each emergent theme.

4.4.3 Causal Mapping & Emergent Themes

In figure 4-5, the prominence is shown through the size of each concept and line weight of each connection. Positive causal connections are blue, and negative causal connections are orange. Common concepts in leverage points, which are the largest in size, include “Education” (n=21), “Number of Local Food Businesses” (n=19), “Producers” (n=13), “Funding + Grants” (n=13), and “Local Food Economy” (n=13). Interventions involving education and partnerships were popular recommendations in this data set, which is also a trend across the Flint Leverage Points Project. Both are generally apolitical interventions – it is relatively low stakes and unproblematic to recommend that behavior might change from learning new things, or that we could move the system forward if we all just worked together. This obfuscates the complexity of both food security and nutrition and the decentralized governance of food systems. As a participant stated, *“*people look at food in two ways, I’ve got to get something in my belly versus I have to get something inside me that’s good for me. So the point may be to just get food in their bellies and the crappier stuff is more affordable…. Education isn’t going to solve that because they don’t have the money. So how can we get more money for food in their pockets?”

Education in isolation cannot address food access and nutritious diets, therefore interventions should also target aspects like physical and economic access to nutritious food. There can also be issues with recommending more partnerships, for example discrepancies in resources or power dynamics. Collaborations, particularly between organizations, can be “band aids” rather than fundamental solutions. Interventions from community-based projects can fail due to lack of involvement of/partnership with relevant community members (Brown & Mickelson, 2019; Hill et al., 2007). To increase likelihood of success, it is important to understand local contexts and engage in ethical and inclusive collaborations with local institutions and community members that is guided by mutual participation, understanding, and ownership (Anderson et al., 2015; Beck & Purcell, 2022; Waylen et al., 2010). Next, we will detail trends within each theme.

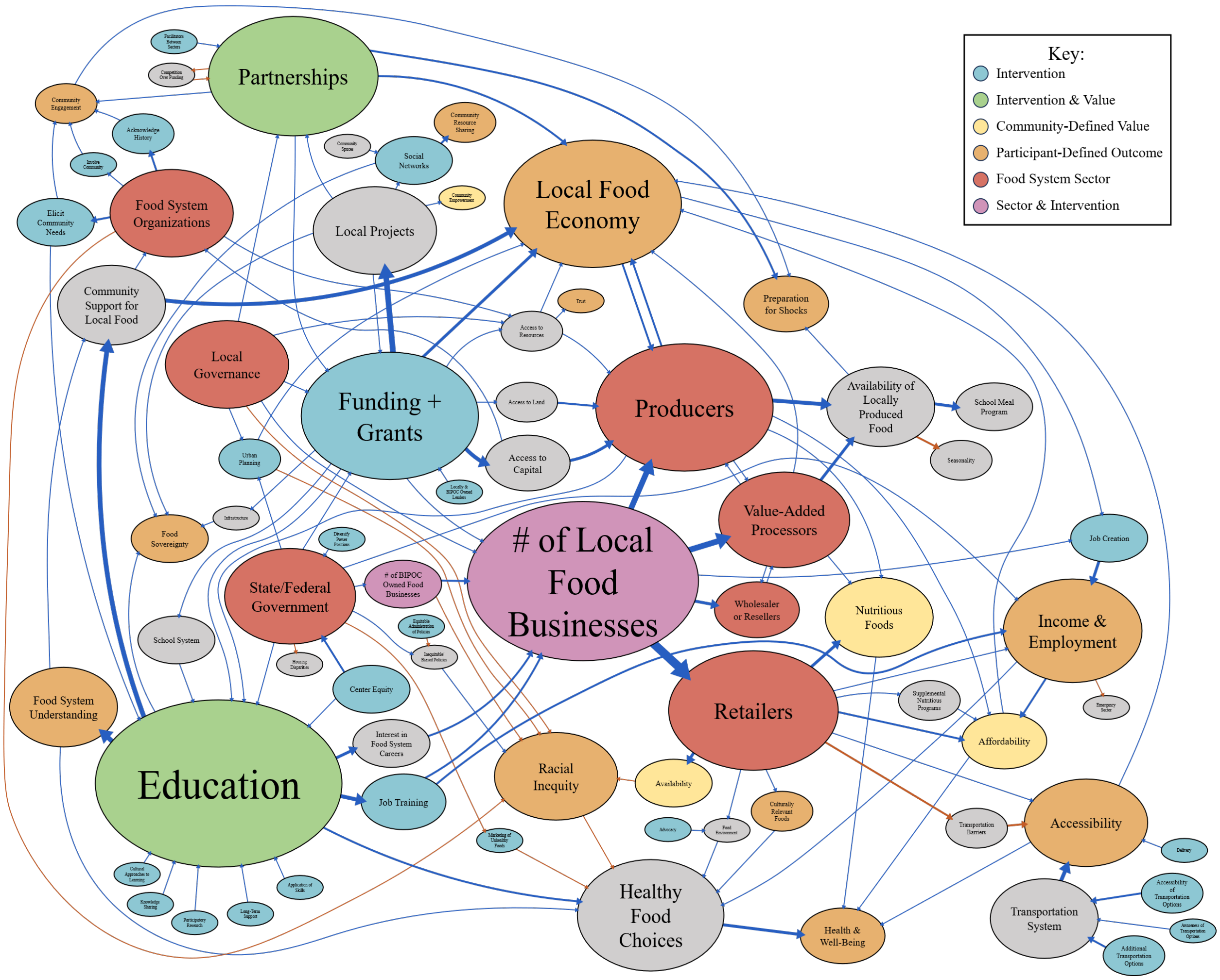


Figure 4-5: Aggregated representation of leverage point causal maps.

4.4.3.1 Local Food Economy

As the most prominent theme across leverage points, mentioned 35 times, strengthening the local food economy was described by participants to be crucial to the success of an equitable localized Flint food system. Promoting BIPOC-owned businesses was mentioned by three participants and was linked to decreasing racial inequity. Many different mechanisms impact the supply side of the local food economy, but prominent levers include investments and other resources such as land or education being made available to entrepreneurs and business owners. Job training and education about food system skills and entrepreneurship, particularly for people under the age of 18, was seen as a critical leverage point to raise interest in careers in the food system, and thus the local food economy. On the demand side, increasing community support for, and thus purchase of, local food was described as an important contributor to the success of local food businesses. Specific ideas ranged from promoting stories about local farmers, to consumer education about the health, environmental, and economic benefits of locally produced foods (see Appendix C for a full list of synthesized statements and causal diagrams).

The outcomes of growing the local food economy were multifold. Firstly, locally owned food businesses were causally linked by participants to local economic growth and increased income and employment. Secondly, local production, processing, and retail can provide fresh, nutritious foods for potentially lower costs, which when combined with local economic growth improves food affordability and ultimately increases community health and well-being. Retail was a common intervention, both to develop the local food economy and to impact food access, which will be discussed more in depth in the "Food Access & Consumption" theme. Third, increasing the number of producers and value-added processors were causally connected to higher availability of locally produced foods and lowering the negative effects of seasonality. The growing season in Michigan is quite short, and value-added processing was described as one mechanism for extending the local food market. Lastly, locally produced and/or processed foods could also be incorporated into the meal programs of the Flint school system.

4.4.3.2 Knowledge

Education, which was regarded by participants as both a lever for change and a desirable food system value in itself, was part of 22 hypothesized leverage points. As previously discussed, two throughlines of this theme were providing job training and education to foster interest in food system careers and increasing community support for local food. The other two main trends were 1) different methods for improving education within and outside of schools and 2) improving community members' understanding of the food system. Several participants described ways to improve educational or instructional practices, such as utilizing cultural approaches to learning, showing hands-on application of skills, prioritizing educational opportunities desired by community members, and having longer term educational programs. Lastly, deeper understanding of the food system was often seen to be a desirable outcome on its own, but two participants also connected this understanding to healthy food choices.

4.4.3.3 Food Access & Consumption

Food security and health are high priorities, and as such several different kinds of interventions fell under the "Food Access & Consumption" theme. Expanding local retail, detailed in the "Local Food Economy" section was commonly linked to improved food availability, accessibility, and affordability in Flint. A few participants (n=2) advocated for additional large grocery stores, but more (n=5) proposed smaller retailers within neighborhoods to address transportation barriers to food access. Other levers to improve the transportation system include additional options, more accessible options, and more awareness of transportation options. The transportation system is highly influential to accessing food retail and participating in the local food system. Another leverage point is delivery of groceries and food. However, other participants remarked that affordability, rather than accessibility, is a barrier to nutritious diets and recommended increasing income and employment. Alternatively, education on topics like cooking or nutrition was linked to healthy food choices. Participants also had specific ideas to target consumption, including changing retail store layouts to promote healthy foods, minimizing the marketing of unhealthy foods, and increasing the availability of culturally relevant foods.

4.4.3.4 Engagement

The “Engagement” theme covers how food system organizations and community members interact and collaborate. Similar to education, partnerships were seen as both a food system value and a lever for change. Two participants described how partnerships between food system businesses in different sectors could increase chances of success. Among food system organizations, partnerships were useful to share information and be aware of others to be better prepared for shocks. Partnerships are diminished through competition over limited grant funding, while partnerships with funders can be critical to securing grants. Participants recommend that food system organizations improve how they engage with community members by acknowledging local history and current inequitable conditions, eliciting community needs, and directly involving community in projects and decision-making. Three participants discussed social networks and mutual aid systems among community members, which is a different perspective on how to distribute resources and move towards food sovereignty. Some mechanisms described by participants include investing in local projects and creating community spaces to encourage social connections.

4.4.3.5 Investment

As participants were actors within the food system, funding and finances were common limitations to their businesses or organizational work. Investment is a critical lever and affects everything from the local food economy to the success of local projects or the school system. Often, the leverage points in this theme were about how government or philanthropic funders could increase investment or redistribute funding towards infrastructure, education, or other areas that support equitable local food systems, but one participant discussed increasing locally and BIPOC-owned lending institutions to increase investments in local projects and businesses. Investment in neighborhoods and local efforts was linked to community empowerment and food sovereignty.

4.4.3.6 Governance

Governance structures, both locally and more broadly at the state and federal levels were commonly the actors responsible for interventions, or the point of intervention to reform current practices. For example, the local government has a lot of power to make changes through utilizing different resources or bringing new ones to the city. Strategic urban planning like zoning changes could increase access to land, support the localized food system, and diminish effects of segregation. As the point of intervention, participants discussed changing how policies were biasedly implemented (for example inequities in grant funding due to structural racism) by diversifying power positions and creating new equity-centered policies that would support local food businesses, education, housing, and racial equity. One participant linked removing barriers to resources to increased trust between governance, institutions, and communities.

4.4.4 Archetypes

We identified two main archetypes from the interview data – “Success to the Successful” and “Shifting the Burden.” Within those archetypes, we found three specific dynamics that can be described by the “Success to the Successful” archetype, and one related to “Shifting the Burden.” This analysis enables us to link interventions described by participants to the dynamics of the Flint food system.

4.4.4.1 Success to the Successful

The “Success to the Successful” archetype depicts two reinforcing loops where resource allocation to one group improves chances of success (see Figure 4-6). This in turn promotes more resources and opportunities to be dedicated to one group, which widens the gap between the successful and unsuccessful. In the context of the Flint food system, this archetype can be used to describe three ways that racial inequity creates disparities for BIPOC community members: barriers to BIPOC-owned businesses, geographic disparities, and health disparities. A critical step to understanding and preventing the “Success to the Successful” archetype is to determine how the system was built to confer privilege to a single group. In the case of racial inequity, the motivations underpinning systemic and structural disparities are clear, but the mechanisms can remain opaque. Structural racism is deeply and insidiously embedded in institutions and programs, whether or not the individuals facilitating them are motivated by interpersonal racism. Structurally informed solutions to this archetype include intentionally allocating resources to the “failing” group, finding ways for the groups to collaborate, and redefining how we view success (Kim & Anderson, 1998).

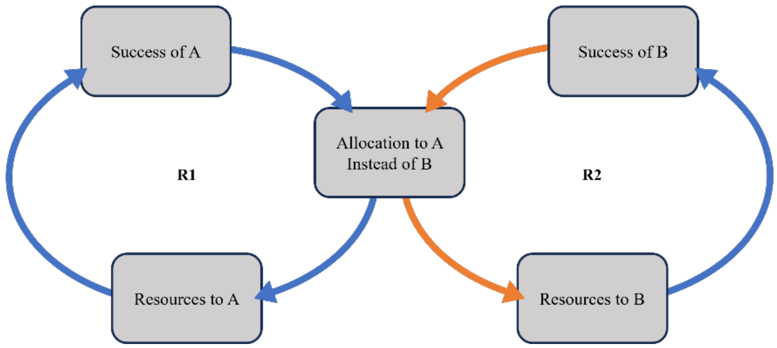


Figure 4-6: Causal loop diagram of the "Success to the Successful" archetype with orange and blue arrows representing negative and positive causal relationships, respectively. Adapted from Kim & Anderson, 1998.

BIPOC-Owned Businesses:

BIPOC-owned businesses encounter numerous barriers to entry and success in the food system, for example access to resources like capital or land. Participants noted a lack of Black-owned businesses and stated, "it comes back to the same kind of underlying both legacy and contemporary patterns of discrimination … people don't have the same access to … financial networks, and collaborations and funders." Producers of color are less likely to receive lending from the United States Department of Agriculture (USDA), which can be a critical source of capital to start food system businesses (Cachelin et al., 2019; Horst & Marion, 2019). Another participant stated, "I know many stories of people in the city of Flint who have tried to purchase property from the land bank, and have been denied for various reasons, but the underlying reason is racial inequity [and] institutional racism." White-owned farms and businesses are more likely to have access to capital, either through grants, investment, or generational wealth, land, partnership networks, and educational training, which results in continued success and higher shares of the agriculture and food industry. Many leverage points address this archetype, with the most prominent theme being "Local Food Economy." Through job training, investment, and other actions like changing zoning laws, this archetype can be allayed by allocating the resources needed to start and build successful BIPOC-owned food businesses.

Geographic Disparities:

Geographic disparities were commonly discussed by interview participants, usually in conjunction with disinvestment and depopulation. Systemic racism, particularly in governance, has furthered economic and quality of life divides in Flint neighborhoods and contributed to spatial inequities to infrastructure and services like retail, transportation, and housing. For example, an interview participant said "[i]f you map retail, you would think that retailers are all explicitly racist, because there's just no chain grocery stores in communities of color." Another commented that "if you have a predominantly white neighborhood or a predominantly black neighborhood, and they're otherwise the same, you'll have fewer community or economic institutions in the black neighborhood. So fewer banks, fewer dentist offices, fewer grocery stores." Investment in predominantly white and affluent neighborhoods increases the desirability of real estate in those areas. It is also more appealing for food retailers and other businesses to be located in areas with higher population density and potential for consumer spending. Leverage points that can address this dynamic include investing in local projects to diminish disparities between neighborhoods, revising zoning laws to encourage development, and creating more locally owned retailers to impact food availability and accessibility.

Health Disparities:

Food access and security have significant implications for health and well-being, in addition to many other pathways that racial inequity reinforces health outcome disparities. As discussed in the previous section, food apartheid and racialized food access inequity impacts the availability, accessibility, affordability, and quality of food for marginalized communities. The theme of “Consumption” targets this dynamic, particularly the linkages between food access and diet-related health disparities. Interventions like creating more locally owned retailers, improving the transportation system, and increasing income and employment are all linked to affordable, accessible, nutritious, and culturally relevant foods. A participant recommended that “[w]e got to be able to have a bus system that routes the residents to have access to a grocery store.… But that's very difficult, trying to load groceries onto a bus, especially in the winter months, and walk a certain amount of distance back to home.” Other consumption-focused interventions include minimizing marketing about unhealthy foods, changing food environments, and increasing culturally sensitive education about health and nutrition. Furthermore, the health effects of shocks like the Flint Water Crisis or COVID-19 disproportionately affect BIPOC communities. Leverage points like equitable community engagement, partnerships, and a strong local food system can lead to preparation for future shocks.

4.4.4.2 Shifting the Burden

The “Shifting the Burden” archetype describes situations where a “quick fix” is used to address problem symptoms, instead of dealing with the real cause. The balancing loop of the fix becomes the main way to deal with the problem, despite not solving the problem, which causes a reinforcing loop as people rely more and more on the quick fix (see Figure 4-7). For the “Shifting the Burden” archetype, solutions often include acknowledging that current fixes are not working and making commitments to implement fundamental solutions which solve the real problem (Kim & Anderson, 1998).

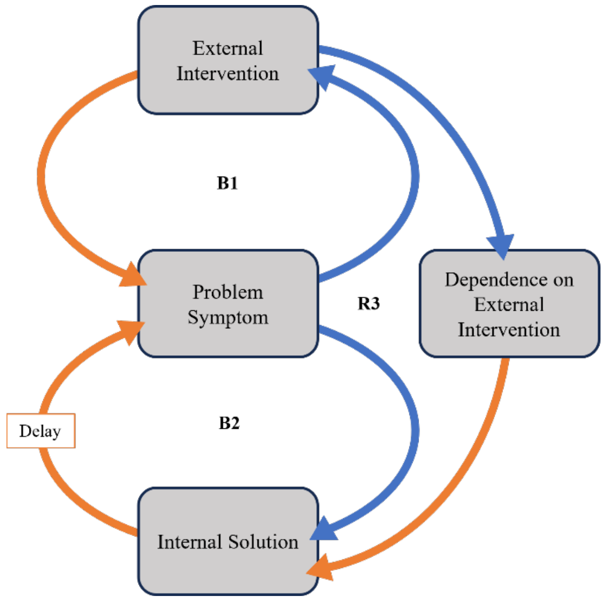


Figure 4-7: Causal loop diagram of the "Shifting the Burden" archetype with orange and blue arrows representing negative and positive causal relationships, respectively. Adapted from Kim & Anderson, 1998

Emergency Food Sector:

The emergency food sector, which provides free food to combat food insecurity, grew rapidly in response to the Flint Water Crisis. This sector provides a valuable resource, but interviewees described a trade-off with lower food quality, limited choice, and low availability of cultural foods from emergency food sources. Specifically, a participant stated that "Flint has a plethora of emergency food options, but none of them are offering things that they would regularly use in their normal day-to-day diet." In addition, the prolific free food options have edged some retailers out of the market. There are long-term concerns over the size and power of the emergency food system, especially regarding the stability of a sector reliant on government or philanthropic funding, and its potential to stunt progress of community-led food sovereignty. The emergency food sector will always be a critical service, as food insecurity can occur without warning, but it is not the fundamental solution to hunger. One intervention specifically deals with this dynamic, and the interviewee says “I think it’s the age-old debate in food banks. Do you just continue feeding people? Or do you try and lift them into that next meaningful, fully engaged citizen that everyone might want to be, right? … How do you have people be ready for the jobs that are available? The economic supports need to be there, whether it be going to college or a trade.” Leverage points like local economic development, ensuring living wages, and improving retail options should be pursued in the long-term to increase access to affordable foods that community members want.

4.5 Conclusions

4.5.1 Recommendations

Based on the synthesis of leverage points elicited from local food system experts and the contextualization of system dynamics from the archetype analysis, actions to improve the outcomes of the Flint food system would include developing the local food economy through levers such as investing capital, providing education and job training on food system careers and entrepreneurship, and lowering barriers for business owners such as access to land. Organizations and governments working towards this goal should ensure that they are eliciting feedback from the community and prioritizing what people actually want. Efforts should particularly focus on supporting BIPOC-owned businesses and work should intentionally and systematically center equity in order to disrupt patterns of racial and ethnic disenfranchisement. Interest in food system careers should be intentionally cultivated, as a participant shared,

> “there is a limited understanding of the farming business … I don't know if it's that we're not cultivating it. I think there is a great amount of interest in business, like entrepreneurship and starting things like food businesses. But in terms of actually getting

> out there, cultivating a plot of land and doing the actual daily work of farming.… [we] have worked with thousands of kids, like nobody said they wanted to be a farmer. I just don't know if that's something that we can talk people into because it's really hard. And there's other stuff that just seems a lot more fun.… It's so important, so important to our lives, but it's a lot more exciting to think about being a business owner or being an attorney or being a doctor or being a nurse or any of those other things."

Strengthening the local food economy has benefits such as increasing the availability of fresh, nutritious, and culturally relevant foods, but supply-side interventions need to be met with demand-side leverage points as well. Locally produced foods can be more expensive because they do not benefit from economies of scale, industrialized processes, subsidies, and other practices that cut costs. In an economically disenfranchised community like Flint, shifting towards localized food without addressing economic development that builds the purchasing power of residents and strength of local businesses may not be a sustainable solution. To truly be a resilient and sovereign local food system, it needs to be physically and economically accessible to residents. Beyond accessibility barriers to participating in the local food system, understanding and valuation of local food can be another limit to consumer demand. Educational campaigns for both adults and youths may aid this goal, as well as creating spaces for communities to build social networks and relationships with food system actors. Ultimately, interventions need to work harmoniously to grow both supply and demand for local produce, value-added products, and retail.

4.5.2 Value & Limitations

A key learning from this project is that if understanding causal reasoning is important, it needs to be addressed during data collection. In settings where narratives or text comes from people, interviewers need to ask interviewees for clarification or justification if that information is not forthcoming. A challenge and limitation of our data set was that participants were asked about leverage points at the end of the interview where they participated in the cognitively challenging task of developing a fuzzy cognitive map. We noted that several participants were more disengaged at this final step. It was a tradeoff that we explicitly considered during the research design phase, but ultimately decided that visualizing their expert understanding of the Flint food system served to both ground participants and create an artifact that could be explicitly used to explore interventions. If the primary research aim is to elicit and evaluate leverage points, we would recommend a shorter modeling session or type of knowledge activation phase before a longer discussion of leverage points. Additionally, it could be valuable to experimentally test interventions in model or, in non-modeling scenarios, have participants theorize about other important information like potential unintended consequences or perceived barriers to implementation.

Another limitation is the sample size. While 24 participants are adequate for most FCM studies, it is relatively few for quantitative comparison. We do not assert that commonly discussed interventions are objectively *better* than other leverage points, but rather focus on trends across the dataset. This limitation could be addressed by expanding the number of interviews or shifting the source of data. There is a wealth of textual data available without interviews from a variety of sources like academic and non-academic texts, websites, social media posts, meeting minutes, etc. Textual data can be used to structure problems within systems and identify elements of interventions like actors, levers, and outcomes to deepen understanding of decision space and tradeoffs. Causal mapping can also be hastened by automation. Techniques like Computer Aided Qualitative Data Analysis Software (CAQDAS) partially automate identification of possible relationships in texts which are then “pruned” by researchers to validate significance and assign directionality (Yearworth & White, 2013). More recently, fully automated causal mapping is being explored by using large language models (LLMs) to extract and typify relationships from textual data (Wadhwa et al., 2023). Natural language processing and other “big data” tools like data mining open up a lot of possibilities for utilizing large data sets that are beyond the resource capabilities of qualitative content analysis. We found value in utilizing a causal mapping approach to structure and aggregate local expert perspectives, and a similar process could be tailored to specific research aims in a surfeit of contexts.

Solution-oriented research emphasizes going beyond understanding system dynamics to taking action towards systemic goals like sustainability, justice, and sovereignty. Systems approaches and inter-/transdisciplinary methods are beneficial to engage actors and develop a holistic understanding of a system from local knowledge, expertise, and preferences. In this paper, we utilized a leverage points perspective to guide elicitation and evaluation of interventions towards racial equity in the Flint, MI localized food system. The process we undertook was elevated by considering a diversity of local expert perspectives, as well as the incorporation of a variety of community goals and preferences when recommending interventions for positive change. Explicitly mapping the concepts and causal relationships involved in interventions enabled aggregation of ideas. Methods like categorizing interventions into Meadow’s (1999) hierarchy of twelve leverage points and/or Abson et al.’s (2017) four characteristics are common when using a leverage points perspective but provide little guidance on how to structurally understand the impact of interventions, quantitatively compare leverage points, or combine interventions at different levels of specificity to maintain data richness. We set out to demonstrate how causal mapping of interventions could deepen understanding of system dynamics, which we further explored through identifying key system archetypes. While moving complex food systems towards racial equity is no small feat, work that is grounded in systems thinking and equitable community participation can provide a useful foundation of system understanding and interventions that are tailored to local dynamics and values.

4.6 Appendices

4.6.1 Appendix A: Semi-Structured Modeling Interview Methodology

4.6.1.1 Data Collection:

The first set of FCM interviews were focused on food insecurity- specifically different sources of food for Flint residents and how those sources influenced food system values. While taking that perspective was important for addressing high-level research questions about the different sectors, critical topics such as racial inequity were not sufficiently addressed. This finding motivated additional data collection centered on racialized inequality and racialized barriers to participating in the localized food system sectors (see Table 4-3).

Table A4-3: Local food system sectors, stakeholders, and definition

Sector:	**Stakeholders:**	**Definition:**
Production	Producers	Growing crops or rearing livestock, can be at any scale from small gardens to large farms
Processing & Packaging	Value-Added Processors	Washing, packing, processing into value-added products
Wholesale & Resale	Wholesaler or Resellers	Gathering then sale of produce or foods by someone other than the producers
Retail	Retailers	Sale of food at stores, markets, or restaurants
Waste	Composters	Collection and management of waste

The format was virtual semi-structured interviews that lasted between 0 and 90 minutes and followed the steps in Figure 4-8. Each interview was facilitated by two research team members, with one asking the questions and the other generating the FCM live with the participant. One interviewer screenshared MentalModeler, an online fuzzy cognitive mapping software, to each participant. As participants were talking, that interviewer added relevant components and connections, routinely verifying that names, connection direction, polarity, and weight were accurately depicting the participant's understanding of the Flint food system. Prior to the interviews, participants were provided with information on informed consent, including any potential risks and benefits to participating. At the beginning of the interview, participants were asked to self-identify if they were a resident of Flint and their role and experience in the food system. Next, interviewers reviewed the definition of each local food system sector to ensure consistent understanding across interviews, and participants were asked to contextualize their expertise across the different sectors.

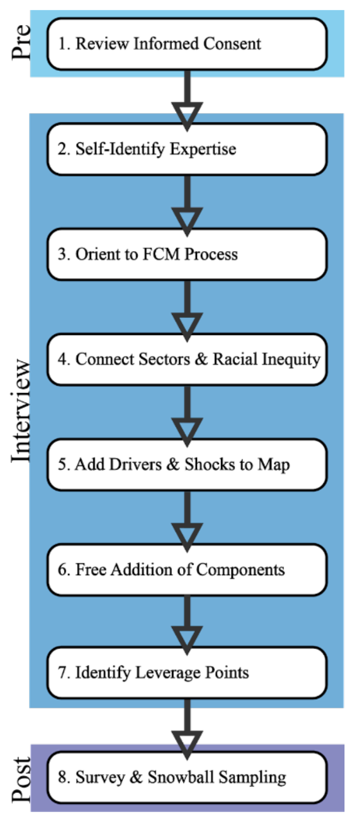


Figure A4-8: FCM Interview Steps

Before eliciting participants' cognitive maps, interviewers used a simple example to explain the processes of creating an FCM with directed and weighted causal connections. Then, the map creation process began with a base map of the five sectors and racial inequity, which the participant drew connections between. Once the participant was satisfied with how they had connected the sectors and racial inequity, they were then asked to add in any major influences on racial inequity. If a participant did not add either the Flint Water Crisis or COVID-19 to their map, they were asked if they wanted to discuss that respective topic. Finally, participants were asked to add any additional components and connections that they believed were important, following open-ended FCM data collection practices (Gray et al., 2014).

After creating their FCM, participants were asked to consider their map and share any hypothesized leverage points for positive change. Changes could be as specific as, "expand food cooperatives across the city to serve other parts and neighborhoods." or as broad as, "push for systemic changes and collaboratively moving the system forward, as opposed to competition and continual grant funding for repeating projects that are band aid solutions." Finally, participants were sent a post-interview survey where they answered demographic questions, recommended other participants, and provided feedback on the interview process.

4.6.1.2 Data Preparation:

The first step to prepare FCM data from individual interviews for comparison is concept standardization. Concept standardization for this dataset was a qualitative and inductive process; two researchers collaborated to standardize all non-base components. The goal of concept standardization is to ensure that comparison across individual maps and aggregation into a collective intelligence map accurately captures the rich qualitative data and narratives behind the

FCM. Standardization can range from correcting simple typos, to assigning the same name to conceptually similar components, or even grouping very specific components into a more representative, properly scaled category. For more information on concept standardization, see Knox et al., 2023. Finally, interview audio was transcribed using Otter.AI and corrected and verified by a researcher for accuracy.

4.6.1.3 Full Interview Protocol:

Research Summary: We want to understand how racial equity impacts participation in local food systems, specifically production, value-added processing and packaging, wholesale or resale, retail, and waste, in Flint, MI.

[Introduction to Interviewer]

Informed Consent:

The informed consent document explains the research and its purpose, that all of your responses will be confidential, any risks or benefits of participating, which is pretty minimal, as well as saying that your participation is completely voluntary. I'd like to record these sessions. The recordings will not be shared outside our research team and are for the purpose of helping ensure we capture everything you're sharing today. Would it be okay if we recorded this meeting?

Thanks for permitting me to record our interview today. The recorder is now on. As a reminder, this conversation is part of our Flint Leverage Points Research Project. Your participation is voluntary, and you can choose not to answer any questions or withdraw from this research at any time. We will keep this recording confidential within our research team and won't use or share your name or identifying information in any of our research results. However, please be mindful of anyone who might be in the room with you or nearby and able to hear your comments. You can follow up with any questions by emailing me, you have my email at. Your consent is demonstrated by your continued participation in this interview. Do you have any questions about this before we move forward?

Section 1: Expertise

Q1: How would you describe your role or multiple roles within the Flint food system?

Q2a: RESIDENT: Are you, or have you ever been a Flint resident?

- How long have you lived in Flint?

Q2b: EMPLOYMENT: So, you mentioned that you worked at/for [name], how long did you work there?

- Did you have other roles there? [If unclear, how many years?]

Q2c: UNPAID: And for the [volunteer work or unpaid work], how long have you been involved?

- Are/Were there other responsibilities you have/had there? [If unclear, how many years?]

[Definitions of Sectors]

Q3: Based on what we just discussed; how do you think about your expertise within the five different sectors? Where do you see yourself having the most expertise?

Section 2: Modeling

Okay, so now we are going to move on to the modeling part of this interview. I will switch screens to the modeling software and give a brief explanation of the modeling process. The software we will be using is called MentalModeler, which was developed as a tool to capture peoples' knowledge and understanding of systems. It's also free to access online.

We're hoping to do a lot of these interviews, get a lot of maps from people, and combine them to basically find a common understanding of the system. Different people think about the system in different ways, and we want to look at where there is overlap. The goal of this interview is to capture how **you** think about the **current** Flint food system. There are absolutely no wrong or right answers.

[Introduction to MentalModeler and FCM using an example about traffic and transportation]

As I said before, there is no wrong or right answer, just what you think. I will also probably ask some clarifying questions, but those will always be to make sure that I am correctly interpreting what you are saying, not that I doubt or don't agree with anything.

Next, I will switch to a map that already has the five sectors we talked about earlier. Before we go into the mapping process, I want to walk through the connections that we have already made and see what you think about the connection strengths.

Q4a: How would you draw connections between the different sectors of the local food system? How would you place yourself or your work into this system?

Q4b: Are there other elements or pieces of the local food system that you want to add?

Do you have any questions?

[Addition of Racial Inequity]

Q5: How would you connect racial equity to the local food system?

Probes:

- What are some ways that racial inequity impacts participation in the local food system?
- What are some racialized barriers to participation in the local food system?
- Are there ways that the food system contributes to racial inequity?

Drivers/Shocks Connections:

Q6: What are or have been some major influences or impacts on the local food system?

Probes:

- How would you connect those to the system?
- [if participant from Flint and not mentioned] How has the Water Crisis impacted the system?
- [if not mentioned] How has COVID-19 impacted the system?
- What do you think are the main sources of or influences on racial inequity in the food system?

Open Addition of Concepts:

Q7: Considering the map that we've made so far: Are there other important or influential concepts you would like to add?

- For example, if we got back to the traffic example, I might add carpooling as something that decreases the number of cars on the road.

Q8: When you look at the model you created, is there anything you think is missing, or that you want to change to better capture how you think about the food system?

Check-In Prompts:

- Okay, so what I heard is a [XYZ] connection from [Q] to [R], is that correct?
- Would you describe that connection from [Q] to [R] or [R] to [Q]?
- Do you think that is a positive connection or a negative connection?
- So for that connection, do you think it is a strong, medium, or weak connection?
- Is the connection I just added correct?
- Great, so how would you turn what you just talked about into a connection? From what node to which other node? Is it positive or negative?

Encourage participants to explain each connection, give the context. Especially if they are not sure about the polarity or direction. If irrelevant to the specific task/goal or does not fit into the model, note the information or potential connection but do not add to the model. Tell the participant throughout that you recorded the information so that it informs both the project and our other interpretations. Provide reminders that they can be honest because the information will be confidential.

Section 3: Leverage Points

The next thing we're going to do is to consider the leverage points, so what changes might improve the system. *[Example using traffic model]*

Q9: So now considering your map of the current local food system, how would you make changes to improve it?

Probes:

- What would be needed to achieve racial equity in the food system?
- What could be done at different levels to get to that goal?
- What could be done in the different sectors to get to that goal?

Section 5: Wrap-Up

Q10: We've talked a lot about different food system sectors, racial equity, and leverage points. Is there anything important about this conversation that I forgot to ask you, or something that you want to add?

[Thank participant, provide evaluation survey, remind of informed consent, invite to reach out with any questions or concerns]

4.6.1.4 Expertise:

Of the 24 local food system experts interviewed, 20 completed the post-interview survey. Overall, participants had more experience in the retail and production sectors, and less expertise in value-added processing, wholesale, or waste (see Figure 4-9). The majority, 16 of the 20 that completed the survey, stated they had more than limited experience in multiple sectors. By nature of the current Flint food system, it was more challenging to recruit participants from certain sectors. Flint has no public or centralized composting infrastructure, and as such the majority of composting that does happen is done by individuals. In addition, the local value-added processing industry is very limited and experienced many challenges during the COVID-19 pandemic.

Figure A4-9: Self-identified sector expertise of interview participants.

4.6.2 Appendix B: Literature Review Results

Table B4-4: Literature reviewed via database search, including classification of the type of document as academic journal articles, technical reports, or mainstream writing such as op-eds, blog posts, policy briefs, etc.

Title:	Type:
A Call to Build Trust and Center Values in Food Systems Work	Technical Report
A community engagement case study of The Somerville Mobile Farmers' Market	Journal Article
A Native perspective: Food is more than consumption	Journal Article
Advancing Racial Equity and Transforming Government: A Resource Guide to Put Ideas into Action	Technical Report
Alternative agrifood projects in communities of color: A civic engagement perspective	Journal Article
An Economic View of Food Deserts	Mainstream Writing
Anti-racist Practice and the Work of Community Food Organizations	Journal Article
Big Ideas Grow from Great Partnerships	Mainstream Writing
Bringing good food to others: investigating the subjects of alternative food practice	Journal Article
Building the Case for Racial Equity in the Food System	Technical Report
Can Farmers' Markets in Shrinking Cities Contribute to Economic Development? A Case Study from Flint, Michigan	Journal Article
Changing the Conversation: Philanthropic Funding and Community Organizing in Detroit	Technical Report
Constructing a Racial Equity Theory of Change	Technical Report
Critical food systems education and the question of race	Journal Article
Decolonizing a food system: Freedom Farmers' Market as a place for resistance and analysis	Journal Article
Delivering More than Food	Technical Report
Emerging assessment tools to inform food system planning	Journal Article
Engaged advocacy and learning to represent the self: Positioning people of color in our contemporary food movement	Journal Article
Finding food assistance and food retailers in Detroit	Journal Article
Food--Systems--Racism: From Mistreatment to Transformation	Mainstream Writing
Food Equity: How Structural Racism Reduces Sustainability in the Food System	Mainstream Writing
Food Insecurity in the Detroit Metropolitan Area Following the Great Recession	Journal Article
Food Solutions New England: Racial equity, food justice, and food system transformation	Mainstream Writing
Food System Racial Equity Assessment Tool: A Facilitation Guide	Journal Article
Injustice on Our Plates: Immigrant Women in the US Food Industry	Technical Report
Is Poverty a Kind of Robbery?	Mainstream Writing
Making visible the people who feed us: Educating for critical food literacy through multicultural texts	Journal Article
Race, ethnicity, and the promise of "Good Food" for Michigan: A three-voice commentary	Journal Article
Racism, food, and health	Mainstream Writing
Rising Wealth Inequality: Causes, Consequences and Potential Responses	Mainstream Writing
The Causes of Racial Disparities in Business Performance	Mainstream Writing
The Characteristics of White Supremacy Culture	Mainstream Writing
The Color of Food	Technical Report
The food system should unite us, not divide us	Journal Article

Three strategies to foster diversity in the food movement	Journal Article
Unearthing the Impact of Institutionalized Racism on Access to Healthy Food in Urban African-American Communities	Journal Article
Unshared Bounty: How Structural Racism Contributes to the Creation and Persistence of Food Deserts	Technical Report
Valuing all knowledges through an expanded definition of access	Journal Article
You Can't Rush the Process: Collective Impact Models of Food Systems Change	Technical Report

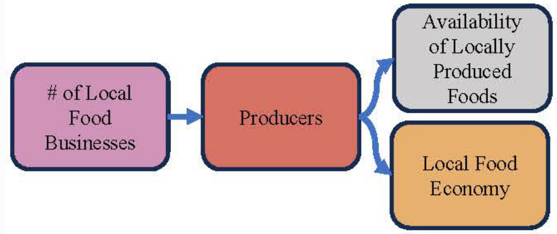
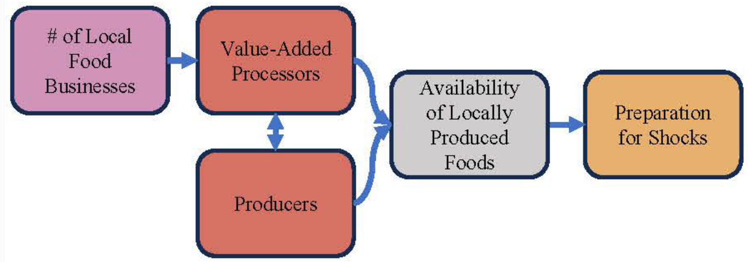
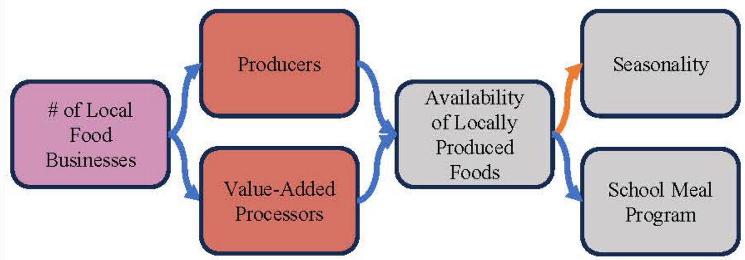
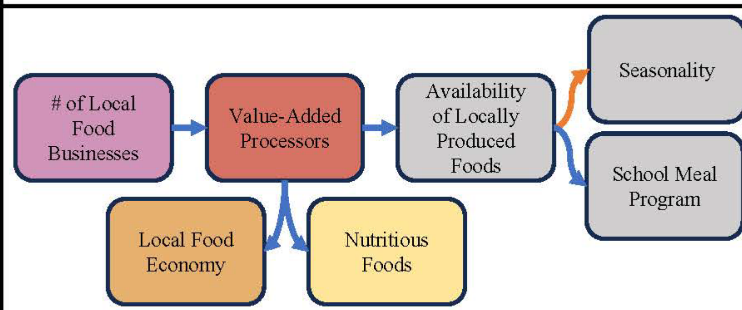
Table B4-5: Racial equity and food systems concepts identified in the literature review. The "count" column shows the number of reviewed articles that contained discussion of each concept.

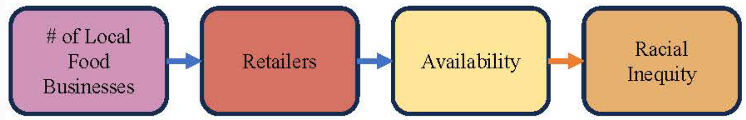
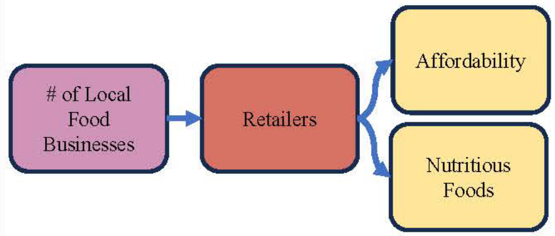
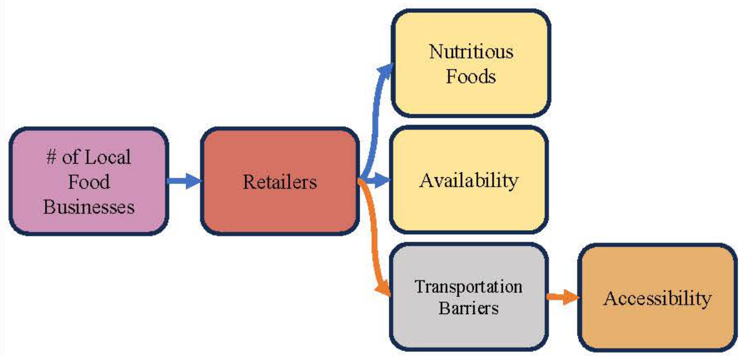
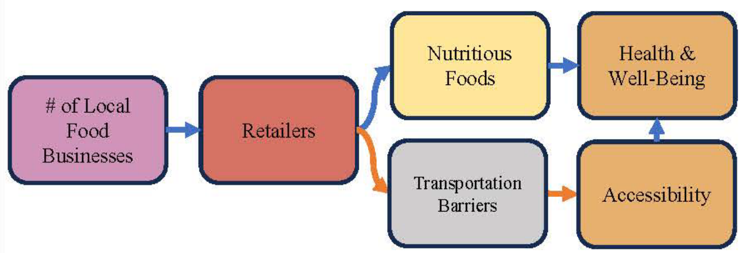
Concept:	**Count:**
Structural Racism/Inequity	21
Government Policies, Programs, and Subsidies	17
Relationships Between Actors	15
Financial Capital	13
Racial Equity/Inequity	13
Health & Well-Being	12
Acknowledgement & Awareness	10
Justice	10
Place Based Strategies	10
Indigenous/Traditional/Cultural Knowledge & Practices	9
Institutional Racism	9
White Privilege	9
Assessment & Evaluation	8
Intersectionality	8
Power Dynamics/Structures	8
Food Deserts	7
Food Security/Insecurity	7
Organizational Dynamics	7
Systems Thinking	7
Bias & Stereotypes	6
Sustainability	6
Anti-Racism	5
Gentrification	5
Labor Rights	5
Retail Sector	5
Transformative Change	5
White Supremacy	5
Collective Impact/Participatory Action	4
Universalism	4
Vertical Integration	4
Food Sovereignty	3

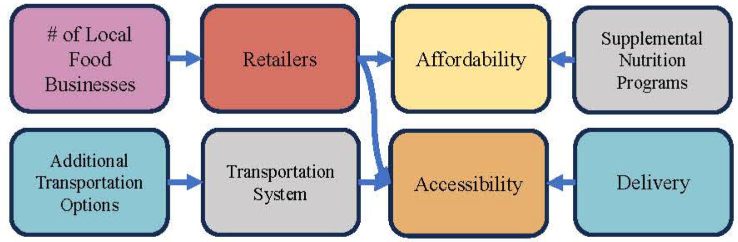
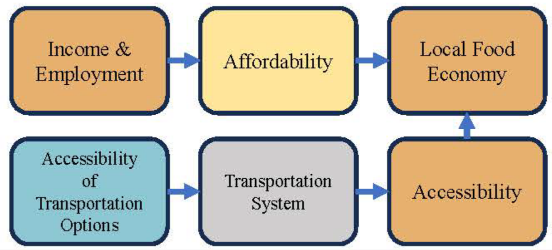
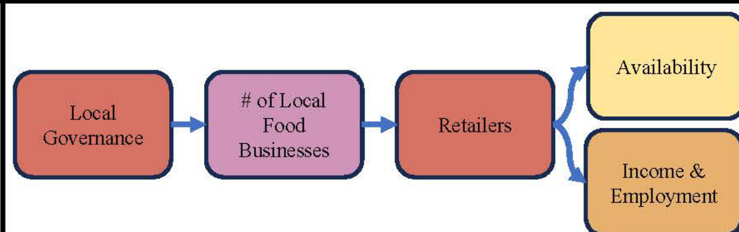
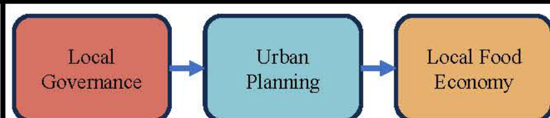
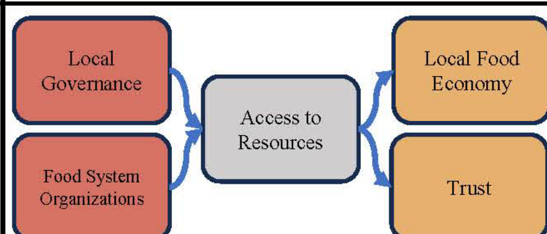
Ownership of Land	3
Racialization	3
Resilience	3
Transportation System	3
Action/Community Based Research	2
Civic Participation	2
Commercial Flight from Urban Communities	2
COVID-19	2
Critical Food Literacy	2
Residential Segregation	2
Tokenization	2
Emergency Food Sector	1

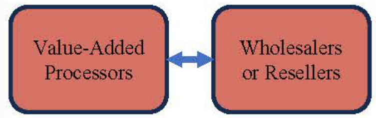
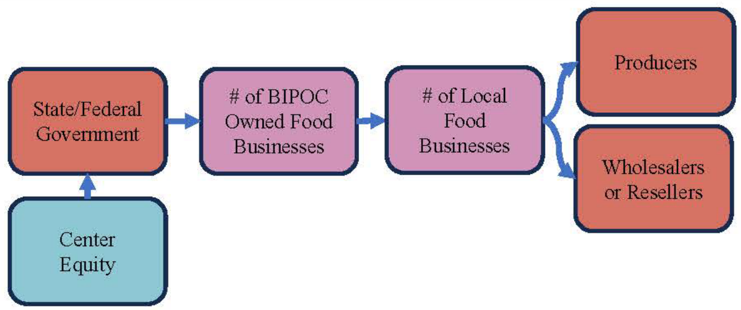
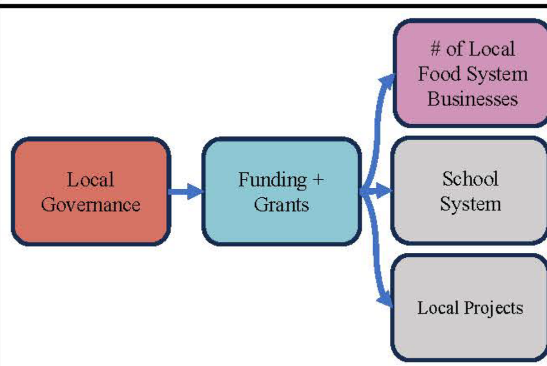
4.6.3 Appendix C: Causal Mapping of Leverage Points

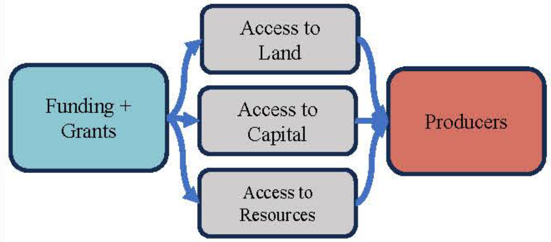
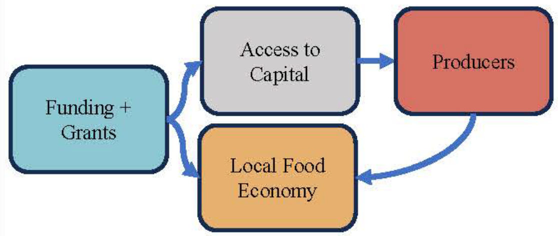
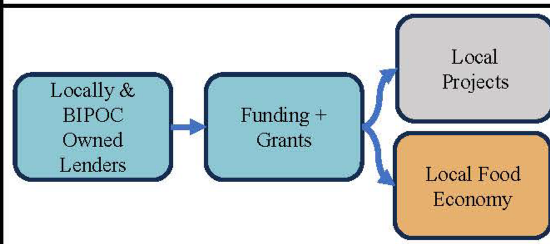
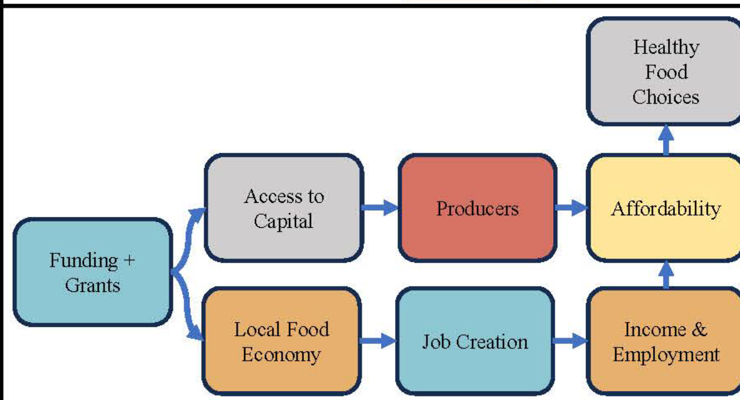
#:	*Synthesis Statement:*	*Causal Mapping:*	*Abson:*	*Themes:*
1	Support local entrepreneurship within the food system.	# of Local Food Businesses	Parameters	Local Food Economy
2	Increase food system businesses that are owned by minorities.	# of BIPOC Owned Food Businesses	Parameters	Local Food Economy
3	Increase the number of food processing plants within the city of Flint.	# of Local Food Businesses → Value-Added Processors	Parameters	Local Food Economy
4	Expand food cooperative stores to serve other parts of the city.	# of Local Food Businesses → Retailers	Parameters	Local Food Economy
5	Create more jobs, within and outside of the food system, to increase income.	# of Local Food Businesses → Job Creation → Income & Employment	Parameters	Local Food Economy
6	Increase producers from marginalized backgrounds to support racial equity.	# of BIPOC Owned Food Businesses → # of Local Food Businesses → Producers; # of BIPOC Owned Food Businesses → Racial Inequity	Feedbacks	Local Food Economy

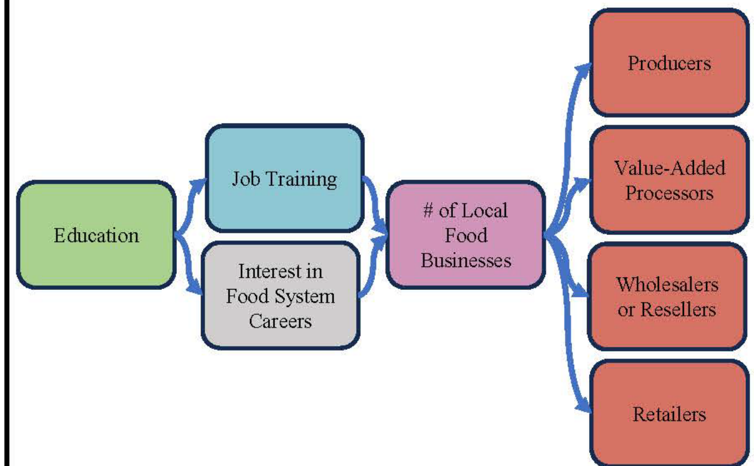
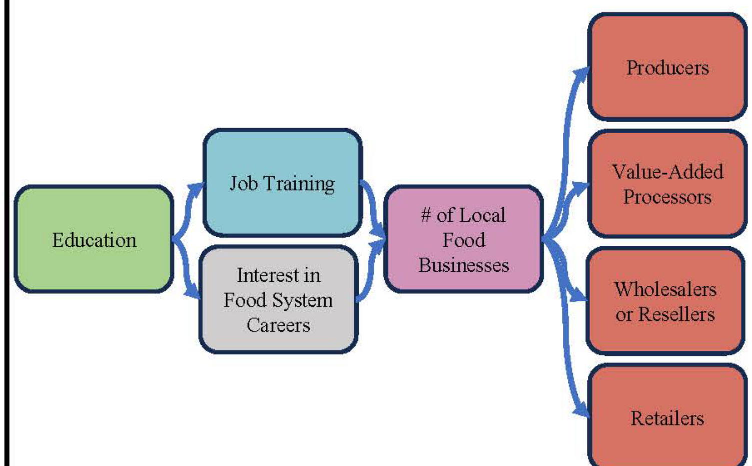
#:	*Synthesis Statement:*	*Causal Mapping:*	*Abson:*	*Themes:*
7	Increase number of local producers to strengthen the local food economy and availability of locally produced foods.		Feedbacks	Local Food Economy
8	Increase value added processing to support and increase local production, that ensures a supply of fresh local food in case of future shocks.		Feedbacks	Local Food Economy
9	Increase number of local producers and processors to supply local produce, to places like Flint public schools, all year long and not just in the growing season.		Feedbacks	Local Food Economy, Food Access & Consumption
10	Increase value added processing to support institutional purchasing and access to healthy foods throughout the year, specifically for places like the Flint public school system.		Parameters	Local Food Economy, Food Access & Consumption

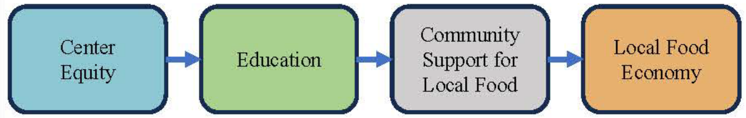
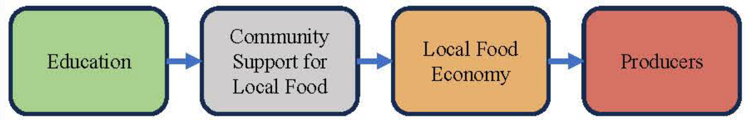
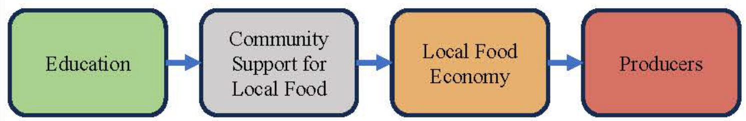
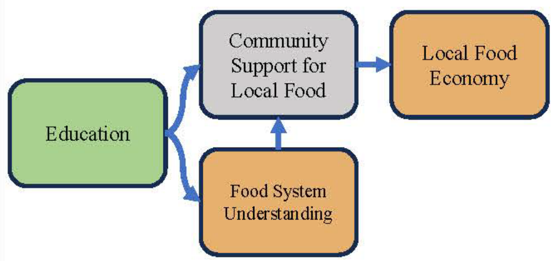
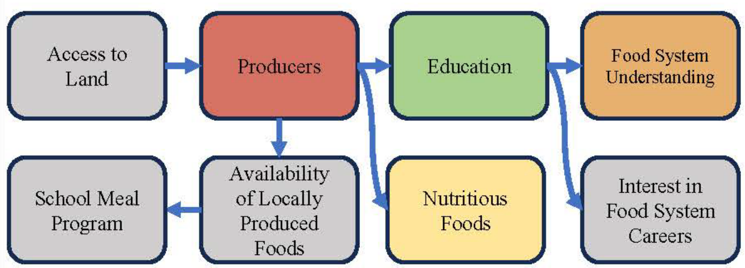
#:	*Synthesis Statement:*	*Causal Mapping:*	*Abson:*	*Themes:*
11	Remove racial inequities by increasing the number of grocery stores and other ways to access food.		Feedbacks	Local Food Economy, Food Access & Consumption
12	Increase retailers in neighborhoods to increase access to fresh produce and affordable foods.		Feedbacks	Local Food Economy, Food Access & Consumption
13	Increase availability of and access to food by creating retail options within neighborhoods, which reduces transportation barriers.		Feedbacks	Local Food Economy, Food Access & Consumption
14	Offer local, quality, and healthy food options within neighborhoods with limited modes of transportation to improve food access and health.		Feedbacks	Local Food Economy, Food Access & Consumption

#:	*Synthesis Statement:*	*Causal Mapping:*	*Abson:*	*Themes:*
15	Increase access to affordable food through new retail, transportation, delivery, or supplemental nutrition programs.		Feedbacks	Local Food Economy, Food Access & Consumption
16	Increase income and access to transportation, to increase ability to participate in the local food system.		Feedbacks	Local Food Economy, Food Access & Consumption
17	Increase number of small neighborhood food stores by city government to increase food access and jobs.		Feedbacks	Local Food Economy, Food Access & Consumption, Governance
18	Make zoning changes to support a localized food system.		Parameters	Local Food Economy, Governance
19	Remove barriers to accessing resources or asking for help to increase participation in the local food system and trust between governance, institutions, and communities.		Design	Local Food Economy, Governance, Engagement

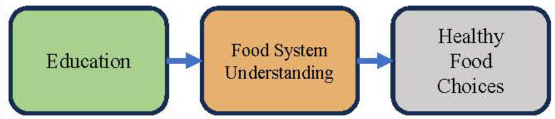
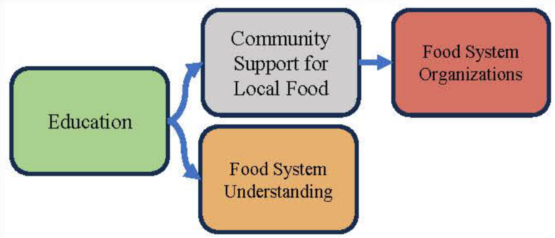
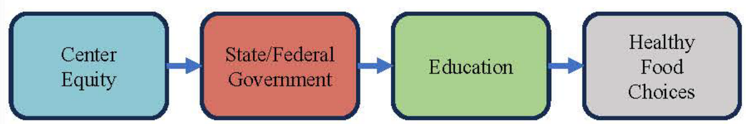
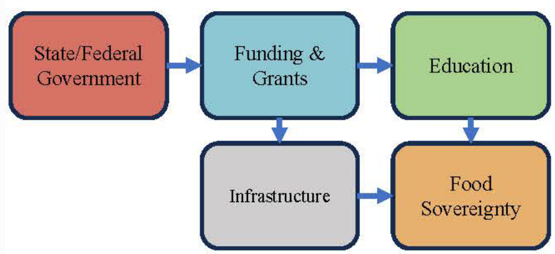
#:	*Synthesis Statement:*	*Causal Mapping:*	*Abson:*	*Themes:*
20	Increased communication between wholesalers and value-added processors to improve how processors are sourcing food.		Parameters	Local Food Economy, Engagement
21	Increase facilitators between new businesses and producers, in order to assist with navigating the local food system, creating partnerships, and increase retailer's chances of success.		Feedbacks	Local Food Economy, Engagement
22	Use food policy to create more connections between producers and business owners to help facilitate local businesses.		Feedbacks	Local Food Economy, Engagement, Governance
23	Implement equity-centered policies to support farmers and wholesalers, especially farmers of color.		Feedbacks	Local Food Economy, Governance
24	City governance uses their power and funding to enact positive change, for example by funding the school system, increasing the number of producers, and bringing state-level resources into the city.		Feedbacks	Local Food Economy, Governance, Investment

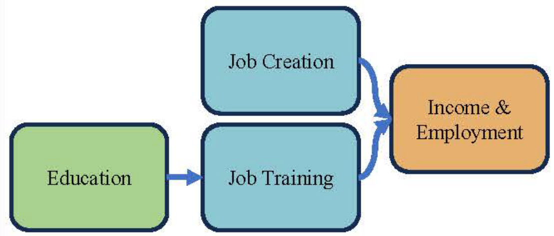
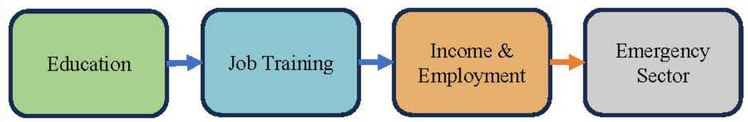
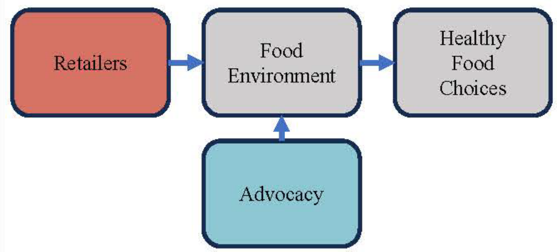
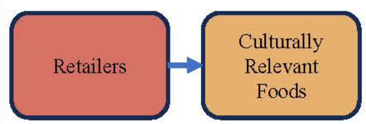
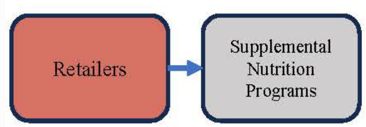
#:	*Synthesis Statement:*	*Causal Mapping:*	*Abson:*	*Themes:*
25	Invest in producers to increase access to land for food production, along with access to resources like capital and equipment.		Parameters	Local Food Economy, Investment
26	Improve funding for long term projects that enact systemic solutions to support producers and develop the local food economy.		Feedbacks	Local Food Economy, Investment
27	Increase locally owned and BIPOC owned lending institutions, as opposed to white dominated and non-locally owned, that would invest more in local projects, businesses, and other efforts.		Feedbacks	Local Food Economy, Investment
28	Expand funding and funding source diversity within food system, specifically for producers, economic development, and job creation. This will close the gap between food price and income so that healthy food is affordable.		Feedbacks	Local Food Economy, Food Access & Consumption, Investments

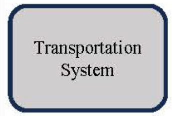
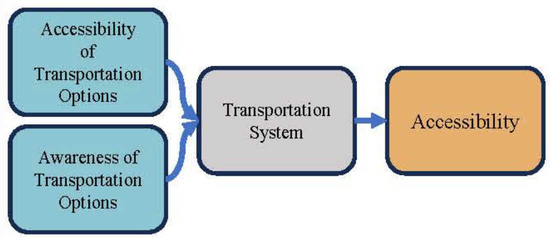
#:	*Synthesis Statement:*	*Causal Mapping:*	*Abson:*	*Themes:*
29	Increase training and education about production or food businesses to lower perceptions of barriers and increase the number of people pursuing food system jobs/careers.		Feedbacks	Local Food Economy, Knowledge
30	Foster interest in farming, businesses, and entrepreneurship among youth, to increase the number of producers and food system businesses.		Feedbacks	Local Food Economy, Knowledge

#:	*Synthesis Statement:*	*Causal Mapping:*	*Abson:*	*Themes:*
31	Increase support for local food economies through education about local histories and destruction of local food economies, specifically by racism and racially-motivated decisions.		Feedbacks	Local Food Economy, Knowledge
32	Support local agriculture by increasing consumer commitment to buying locally source products, for example by communicating aspects like organic produce that increase willingness to pay.		Feedbacks	Local Food Economy, Knowledge
33	Promote and market stories of local producers to increase awareness of and support for farming and local food.		Feedbacks	Local Food Economy, Knowledge
34	Strengthen the local food system by increasing community support through interventions like food systems education to strengthen knowledge of and pride in locally produced/processed foods.		Feedbacks	Local Food Economy, Knowledge
35	Utilize available, open land to produce vegetables that could improve school lunches and be used to teach children about agriculture and the food system, which could become a career.		Feedbacks	Local Food Economy, Knowledge, Food Access & Consumption

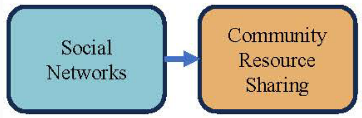
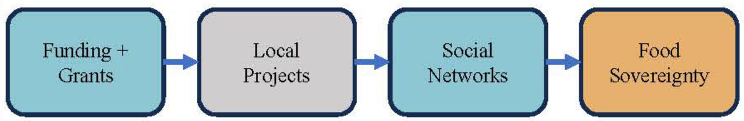
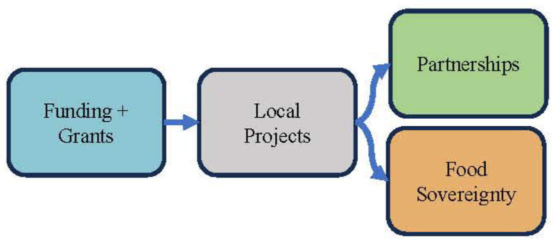
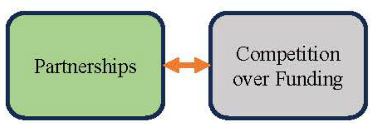
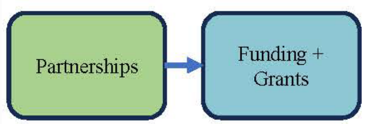
#:	*Synthesis Statement:*	*Causal Mapping:*	*Abson:*	*Themes:*
36	Target impacting education to create sustainable change.	Education	Parameters	Knowledge
37	Increase education efforts.	Education	Parameters	Knowledge
38	Provide long-term access, support, and follow-through on education to ensure systemic change at the community and local system level.	Long-Term Support → Education	Feedbacks	Knowledge
39	Improve education by not just providing basic level education to people, but skill sets and showing application of those skills.	Application of Skills → Education	Feedbacks	Knowledge
40	Prioritize education that is wanted by community members.	Elicit Community Needs → Education	Feedbacks	Knowledge, Engagement
41	Improve the Flint school system.	School System	Parameters	Knowledge
42	Increase education through school programs along with sharing knowledge at home/among generations.	School System → Education; Knowledge Sharing → Education	Feedbacks	Knowledge

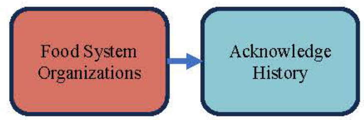
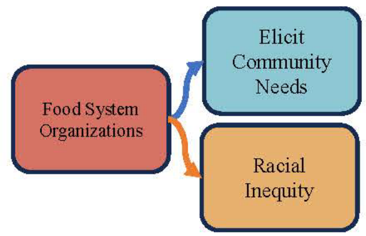
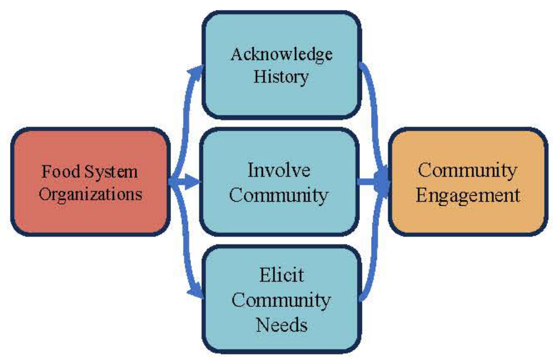
#:	*Synthesis Statement:*	*Causal Mapping:*	*Abson:*	*Themes:*
43	Include culture/cultural approaches in general food education to increase the effectiveness of lessons on healthy eating.		Feedbacks	Knowledge, Food Access & Consumption
44	Increase public education on food labels and differences in food quality for a deeper understanding of choices available.		Feedbacks	Knowledge, Food Access & Consumption
45	Incorporate more community participatory research and communicate it to public to increase access to information and food system understanding.		Parameters	Knowledge, Engagement
46	Continue educational outreach, exposing youth to the food system and gaining community support of food system organizations.		Feedbacks	Knowledge, Engagement
47	Center anti-racism work in governance and policies so that racial equity will be a focus throughout and feed into other spaces like education and nutrition.		Intent	Knowledge, Governance, Food Access & Consumption
48	Address economic inequality through federal policy (tax increases for upper brackets, decreasing the defense budget, etc.) to allocate funding other places like infrastructure and education, which would allow for the food system to fix itself.		Design	Knowledge, Governance

#:	*Synthesis Statement:*	*Causal Mapping:*	*Abson:*	*Themes:*
49	Offer job training programs with successful placements and other opportunities that provide meaningful employment with livable wages.		Feedbacks	Knowledge
50	Think beyond emergency services by providing job training and economic support that lifts people up and breaks the emergency food cycle.		Intent	Knowledge, Food Access & Consumption
51	Advocate for changes to retail experience to benefit both retailers and community of consumers, such as redesigning layout of store to promote healthy options		Parameters	Food Access & Consumption
52	Increase availability of culturally appropriate foods in retail stores		Parameters	Food Access & Consumption
53	Promote and prioritize culturally relevant foods to improve nutrition and health.		Parameters	Food Access & Consumption
54	Increase acceptance of supplemental nutrition programs in local stores.		Parameters	Food Access & Consumption

#:	*Synthesis Statement:*	*Causal Mapping:*	*Abson:*	*Themes:*
55	Improve the transportation system.		Parameters	Food Access & Consumption
56	Offer more bus routes specifically to retailers like grocery stores and the food co-op.		Parameters	Food Access & Consumption
57	Increase accessible transportation options, and awareness of options, to improve how people are accessing food.		Parameters	Food Access & Consumption
58	Create policies or requirements to minimize the marketing of unhealthy foods.		Parameters	Food Access & Consumption, Governance
59	Address health disparities from racial inequity, for example chronic illnesses like diabetes and heart disease from poor diet.		Feedbacks	Food Access & Consumption
60	Change food consumption habits by increasing income/wealth rather than education, as affordability is a major factor in purchasing unhealthy foods.		Feedbacks	Food Access & Consumption

#:	*Synthesis Statement:*	*Causal Mapping:*	*Abson:*	*Themes:*
61	Create more opportunities for networking and partnerships.	Partnerships	Parameters	Engagement
62	More collaboration between organizations, increase awareness of what everyone's doing.	Partnerships	Parameters	Engagement
63	Greater connectivity to share knowledge sharing among partners.	Partnerships	Parameters	Engagement
64	Convene and support partnerships.	Partnerships	Parameters	Engagement
65	Improve and expand partnerships.	Partnerships	Parameters	Engagement
66	Increase communication between organizations to prepare for shocks and future events	Partnerships → Preparation for Shocks	Feedbacks	Engagement
67	Normalize and revitalize strong community partnerships to improve engagement, build community, and withstand shocks.	Partnerships → Community Engagement; Partnerships → Preparation for Shocks; Community Engagement → Preparation for Shocks	Design	Engagement

#:	*Synthesis Statement:*	*Causal Mapping:*	*Abson:*	*Themes:*
68	Utilize strategies from social networks and mutual aid systems to solve problems.		Feedbacks	Engagement
69	Identify or create a common place to allow for social interactions and access to resources and support.		Feedbacks	Engagement
70	Utilize funding opportunities for community projects and events in order to build community support networks/partnerships and reach a point of self-sufficiency		Design	Engagement, Investment
71	Increase support for small, local programs to ultimately create self-sufficient programs that address different pieces of the food system and have a large positive impact through increased control, autonomy, participation, and partnerships.		Design	Engagement, Investment
72	Push for systemic changes and collaboratively moving the system forward, as opposed to competition for grant funding.		Design	Engagement, Investment
73	Increase funding through partnerships with funders.		Parameters	Engagement, Investment

#:	*Synthesis Statement:*	*Causal Mapping:*	*Abson:*	*Themes:*
74	Institutions and organizations should directly acknowledge local history, discrimination, and trauma caused to community members.		Design	Engagement
75	Organizations should recognize the needs of the community and act on the big problems of racial equity, rather than focusing on smaller issues.		Intent	Engagement
76	Improve community engagement by acknowledging how history and current conductions influence lived experiences, and by involving local community and asking them directly what their needs are (including acknowledging local and traditional knowledge).		Design	Engagement
77	Increase philanthropic funding for operational support for programs, rather than just programming, to increase equity between organizations and fill gaps created by inequitable access to capital.		Parameters	Engagement, Investment
78	Secure funding and financial support (fundraisers, grants, etc.) to address food system issues		Parameters	Investment

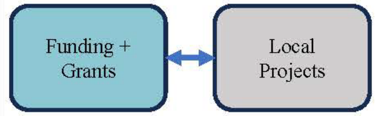
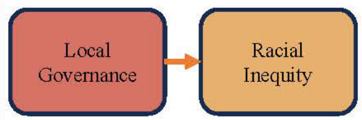
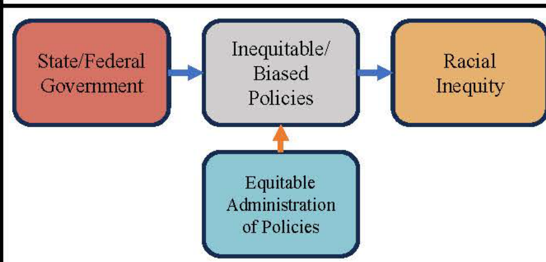
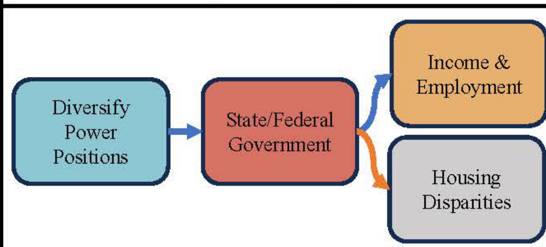
#:	*Synthesis Statement:*	*Causal Mapping:*	*Abson:*	*Themes:*
79	Pursue long-term projects of success to demonstrate viability of investing in local businesses to larger investors and opens the door to more investments.		Feedbacks	Investment
80	Invest in neighborhoods, to bring outside people into Flint and to support existing communities.		Parameters	Investment
81	City government should explore disconnects, issues of access, and racialized barriers to address racism as a public health issue.		Intent	Governance
82	Centralize the approach to urban planning (for example, changing state land use law around development) to eliminate the effects of segregation and discrimination.		Design	Governance
83	Change administration and implementation of biased policies, to better serve all populations in the community and promote equity.		Design	Governance
84	Refine the legislative body and diversifying power positions to address deeper, systemic issues such as inflation, poverty and homelessness.		Design	Governance

Figure C4-10: Causal mapping of synthesis statements with coding for Abson categories and emergent themes.

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Chapter 5 Conclusions

5.1 Lessons from Food System Modeling

It is difficult to underestimate the complexity of the food system, and yet it is a vital area for sustainable transformation. Through my research about the Flint, Michigan food system, I explore how participatory modeling can be used to deepen system understanding based on expert and local knowledge and evaluate interventions. I have demonstrated the potential of fuzzy cognitive mapping for transparent and community-engaged research, but I also want to reacknowledge the limitations. FCM cannot manage temporal or spatial dynamics, non-linear relationships, or provide scenario results with units – all of which might be vital information for decision-makers. Participatory modeling is a process, and you need the right tool for the job.

One of the most important steps in the modeling process is problem articulation. It can be tempting to gloss over this step, to jump into the fun part of putting down concepts and stringing connections, but the reality is that developing a good understanding of the system being studied and grounding your modeling efforts dramatically improve the likelihood of success. What are the limitations? What is an appropriate scope? Is this even a problem or a system that can be modeled? What kind of modeling is appropriate to answer your question? In teaching about complex systems and modeling, I often remind my students of the common aphorism that "all models are wrong, but some models are useful." To be useful, a model needs to address a specific and clear purpose, so we can select the right method, set a scope, determine what is important, and plan an analysis.

In Chapter 2, I inventoried and mapped relationships between sustainability outcomes in the U.S. food system from academic literature. This qualitative model (Figure 2-4) provides an overview of key outcome categories and interconnections between them. The primary goal is communication rather than simulation. At the national level, it would be extremely resource-intensive to create a meaningful parameterized model of how the food system results in sustainability outcomes, based on both the complexity of spatial and temporal variation in regional food systems, and limited data availability. A qualitative model is well-suited to visually represent generalized connections between outcomes, as the purpose is to provide a potential starting point for further analysis or modeling. Depending on the specific research question or study system, investigators could use the diagram to start from a holistic conceptualization before narrowing to the most relevant, closely connected food system outcomes.

The modeling in Chapter 3 focused on understanding how different sources of food in Flint related to community-defined food system values. The collective intelligence model (see Figure 3-12) is tailored to the dynamics of the local food system, so not all findings can be extrapolated to other food systems. A parsimonious model for this study context balances both visual simplicity for communicating with diverse audiences of community members, while maintaining enough dynamic complexity to run a variety of "what if?" scenarios. One of the benefits of semi-quantitative modeling is the ability to test potential changes or interventions through scenarios. The results are relative and without units, but the models also capture participants' values and preferences which is generally not a quantitative evaluation. While there is a loss of quantitative data, I have found that there is value to creating models that can simultaneously represent objective and subjective relationships. It is useful to be able to seamlessly ask community members how a zoning policy impacts both the amount of land being used for urban agriculture and their sense of community cohesion. When scenarios are run, the results reflect the system but also the wants and fears of the people who shared their knowledge – which are both relevant to making effective and equitable decisions.

Chapter 4 synthesizes leverage points towards racial equity in the localized food system into a causal diagram (see Figure 4-5). The primary benefit of this form of mapping was the ability to visually represent a diverse set of perspectives while maintaining data fidelity. The prominence of different concepts and connections were represented graphically, which pulls viewers' eyes to commonly discussed interventions. The scope of the leverage points diagram, focusing on lever pullers, levers, and outcomes, is also useful when considering different alternatives or potentially portfolios of interventions. It can be easy for stakeholders or decision-makers to get bogged down in the details of complex systems. Removing an emphasis on dimensions like the physical food system or spatial dynamics enables more cognitive energy to be spent on solution-oriented innovation. One key trade-off of this approach to modeling is between analytical capability and data requirements. Inferring causal relationships from narrative or text data is applicable to many contexts and data sources, while assigning connection strengths requires additional information but does enable scenario analysis.

In summary, the food system is complicated, and uncertain, and requires coordination between distributed decision-makers to enact change. Models are amazing tools for managing complexity and minimizing uncertainty, but they are inherently simplifications of reality and thus are never perfect. For novice modelers, it can be a paradigm shift to strive for usefulness instead of perfection. Usefulness is dynamic and contextual – there is no single model or diagram that is well-suited for all contexts. The success of food system modeling is determined by how accurately questions are answered or how effectively information is communicated. In many ways, food systems research is very practical, with emphasis on application and creating real-world change. I have found that modeling and community-engaged work are wonderfully complementary to the meaningful study of complex food systems.

5.2 Lessons from Community-Engaged Research

Beyond the academic results of my research in Flint, Michigan (chapters 3 and 4), I want to share five of the "soft" findings from being part of a long-term community-engaged research project.

[1] Build enduring and mutually beneficial collaborations with strategic partners. Our community partners were the most invaluable asset; their guidance and feedback throughout the process of research design, execution, and dissemination were critical. However, many of the partnerships were not cultivated for this specific project but grown through years of collaborations between the academics and food system organizations. Having long-term relationships enables both parties to reach out with opportunities and can spark new solution-oriented work. When establishing partnerships, consider questions such as: who are the relevant players? Who holds decision-making power? Who is not in the room, and why were they not invited? It is also important to meaningfully engage with partners in a way that is mutually beneficial and does not just tick the box of participatory research: establish partnership agreements, articulate responsibilities, and make explicit how all parties will benefit. Successful partnerships will improve both research outcomes and impact of work. Given the comparatively short-term nature of research projects, it is vital that partners feel ownership over research and the knowledge generated, so they can carry those learnings into the future and apply them towards positive change.

[2] Be aware of power dynamics and your own social identity. It can be tempting to consider yourself as a researcher to be a neutral party, but science and research are inherently political. You should be aware of potential power dynamics and how they impact data collection. For example, an employee might censor themselves if their boss is partnering on the research. An organization might downplay challenges or barriers they have faced or exaggerate the effectiveness of their programming if the results might impact the allocation of grant funding. Being aware of these dynamics can inform how you conduct and facilitate research. Particularly in cities like Flint which are highly studied and/or have been historically mistreated by academia, community partners can better reach people because of factors like trust, name recognition, or their established personal/professional networks. In regard to social identity, I have found it best to acknowledge the relationships between facilitators, participants, and the system being studied. As a white researcher stepping into a predominantly Black community, my social identity impacts how people perceive me and our interactions in interviews. I had participants apologize for their critiques of white supremacy by saying things like, "I know you're not like that." If the goal is open and honest dialogue, researchers need to be aware of these dynamics and establish ways to productively manage them.

[3] Those with the most first-hand knowledge can have the least resources – honor their investment. Participant recruitment can be challenging no matter the context but, in my experience, it is particularly tough to engage with groups and individuals at the frontlines of sustainability work. In our case of the Flint food system, grassroots community organizations and local business owners were difficult to recruit. Being part of research is not part of their jobs, and they have very limited time to devote to anything that does have a clear benefit for them. Financially compensate them for their time if you are able by writing those costs into

community-engaged research grants. If doing so is not possible, be clear about how the research will impact them and devote time to creating relevant non-academic products. Be flexible with timing and engagement format. I have done interviews over the phone while people were cooking or took a half hour pause so they could put their kids to bed. Optimally, participants would be purely focused on the interview, but I have found that a suboptimal interview is superior to entirely missing the knowledge of those who are doing you, the researcher, the biggest favor by participating at all.

[4] Your first "big finding" will be obvious – keep going. As an outsider and novice to a system, it is exciting to start putting the pieces together into a more comprehensive picture of dynamics and begin noticing trends. My first research findings presentation to our panel of community partners was distinctly underwhelming – their reactions were essentially, "Yes, we know all this." Do not get discouraged, this is the result you want! At these early stages, you should be developing an understanding of the system that is inherently recognizable to your partners and the community. They should be able to see their knowledge and lived experiences reflected back at them. Push that learning deeper, explore new analytical approaches, and talk to more people – but start from that foundation that is "obvious" to the people who work, manage, and live in your study system.

[5] Prioritize community outcomes. Lastly, but perhaps most importantly, resist the flows and pressures of academic systems when they do not complement community outcomes. Academic timelines might fit neatly into semesters, but those divisions can be irrelevant to partners. Spring could be the optimal time for students to collect data for their capstone projects, but that is the busiest time for farmers. Researchers might prefer to plan events during normal working hours, but equitable community engagement will more likely happen after five pm or on

weekends. Our success is often defined by academic publications, but those can be deeply inaccessible for community members. Prioritize the generation of accessible community products; publish in open access journals, but also write policy briefs or community notes. Create different forms and venues for science communication and research engagement, and if you do not know how to do so contextually: ask people what would be helpful.

5.3 Research Directions

There are three main lines of inquiry that I propose for future research efforts: 1) strengthening the theoretical underpinnings of participatory modeling, 2) expanding methodological capabilities, and 3) applying participatory modeling to create change. FCM is a relatively new approach and will benefit greatly from continued iterative and coupled advancement of theory, methods, and practice. A strong theoretical basis allows researchers to innovate, which in turn bolster opportunities of application.

Participatory FCM hinges on the idea that people hold mental models in their heads, and that through facilitation they can be externalized. However, cognition can differ between individuals. How can accurate FCMs be created from participants who think more in narratives or pictures? How should facilitation practices be shifted if systems thinking and/or visualization into a graphical network is ill-suited for a particular interviewee? Limited work has been done to evaluate how elicitation methods can impact the accuracy of external FCMs to a participant's internal mental models, which is an important step to minimizing sources of modeling error. In addition, a future area for theoretical development is how to validate participatory models. In Chapter 3, I found that when participants held many sources of knowledge, identity diversity (job, role, etc.) is a poor proxy for knowledge diversity (conceptual understanding of the system).

By comparing aggregation methods based on quantitative and qualitative performance metrics, we found that the more accurate, parsimonious model was generated using conceptual coding and principal component analysis to group participants. More research is needed on how to validate both sources of data and final models, especially with limited resources or situations like shocks with short time constraints.

The next line of inquiry, expanding methodological capabilities, is aimed at increasing the toolkit for participatory modeling use and analysis. One rapidly developing frontier is the use of large language models in conjunction with modeling. Natural language processing and FCM could be used to automate knowledge curation to assess variation in causal reasoning and typify perspectives on complex systems. Contrasted to the process of concept standardization, categorization, and aggregation in Chapter 3, this approach would greatly reduce the amount of labor involved in data standardization and analysis and provide a fast way for facilitators or decision-makers to get feedback on differences in system understanding and preferences. Another area for methodological innovation is creating subgraphs from rich FCM data. Through conversations with Flint community members and partner organizations, it became clear that while the aggregated model was useful from a holistic perspective, people also wanted models of their specific sector or area of expertise. A method for "zooming in" on an aggregated map to focus on a specific area and reintroduce data richness does not currently exist. My next research endeavor will be developing and testing a novel method of subgraph creation that incorporates both graph theory and multi-criteria decision-making to allow users to tailor subgraphs to their needs.

Lastly, increasing application of participatory modeling for positive change will require lowering barriers for use of participatory modeling for researchers, practitioners, and decision-makers. Participatory research is fundamentally a tool, and has tremendous potential to generate change, in part due to decision-maker engagement and increased transparency, but more work is needed to demonstrate the effectiveness of participatory models as a decision support tool in a variety of applications. In Chapter 3, I demonstrated how local perspectives on potential leverage points can be elicited and evaluated in terms of structural dynamics, but this work will be expanded upon to include scenario analysis to identify benefits, trade-offs, and synergies. FCM can also be integrated with other modeling techniques like Agent-Based Modeling or benefit-cost analysis to provide additional inputs that may be important to decision-makers, like spatial dynamics or return on investment. Future work that would complement increased application could include evaluating the impact of participatory modeling on decision-making quality and social learning. Long-term, my goal is to improve the capability and effectiveness of participatory modeling to reduce resource input and effectively inform sustainable decision-making.

5.4 The Future of Sustainability

I want to conclude this chapter with a reflection on sustainability science and its role in modern society. The origin of the field- to understand and solve sustainability problems- is untraditional for academia and a source of critique. Following the trend of exponential growth of sustainability work over the last two decades, the field will likely find acceptance in the next decade, but currently, it often requires justification. Interdisciplinarians face challenges such as resistance to change, academic gatekeeping, and difficulties validating interdisciplinary knowledge creation by disciplinary criteria (Nissani, 1997; Weingart, 2000). There are also concerns internal to sustainability science about inclusion and valuation of economic and social sustainability, or linkages between health and sustainability (Davidson, 2009; Dora et al., 2015; Kjærgård et al., 2014; Newell, 2010).

These critiques are not unfounded – inter-/transdisciplinarians must properly ground their approaches in theory and methods. In Chapter 2, I showed that many ostensibly "interdisciplinary" studies utilize disciplinary lenses that shape how they conceptualize the food system, develop interventions, and measure success in terms of limited sustainability outcomes. While there are still areas for improvement, I believe these concerns are overshadowed by the immense potential of spanning disciplinary boundaries. It is a both/and situation – we need specialists to dive deep into topics and fields, to pursue new knowledge at the fractal edges of disciplines. We also need interdisciplinarians to forge across fields, to bring in fresh insights, spark innovation, and address complexity.

A core argument of my research is that sustainability in complex socio-environmental systems can only be effectively addressed using system approaches, the integration of disciplinary knowledge and methods, and collaboration with stakeholders. The urgency of existential sustainability challenges like climate change, food security, or poverty underscores my emphasis on applied work that is explicitly linked to change. We need transformative change – a profound shift in interactions and feedbacks that promote well-being, resilience, and justice for humans and nature (Bennett et al., 2019; Hölscher et al., 2018; Scoones et al., 2020). Through this dissertation, I explored how participatory modeling can combine the strengths of interdisciplinarity, systems approaches, and transdisciplinarity to understand and solve problems in complex adaptive socio-environmental systems. Solutions and interventions developed using this process are more likely to be fundamental solutions – by identifying and addressing or avoiding unintended consequences and system traps – that can effectively enact meaningful change towards sustainability and justice.

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