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Exploring the Barriers to and Potential for Sustainable Transitions in Urban–Rural Systems through Participatory Causal Loop Diagramming of the Food–Energy–Water Nexus

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Abstract: Understanding Food–Energy–Water (FEW) systems is crucial in order to plan for a resilient and sustainable future of interdependent urban–rural regions. While research tends to focus on urban transitions, the topic remains understudied relative to urban-rural regions. The often conflicting pressures in these regions (e.g., urbanization and growing crop production) may pose distinctive challenges where large urbanizations are adjacent to sparsely populated rural areas. These systems may further shift in response to local and global economic and demographic trends, as well as climate change. Identifying these complex system trajectories is critical for sustainability and resilience planning and policy, which requires the pooling of both urban and rural expertise across multiple disciplines and domains. We convened panels of subject matter experts within a participatory causal loop diagramming (CLD) approach. Our workshops were facilitated by our research team to collaboratively construct the web of connections among the elements in the urban–rural FEW system. The CLDs and the discussions around them allowed the group to identify potentially significant lever points in the system (e.g., support for minority farmers to enhance food security while reducing waste), barriers to sustainability (e.g., laws restricting the sale of water treatment biosolids), and potential synergies across sectors (e.g., food and green energy advocacy jointly pressing for policy changes). Despite the greater understanding of urban–rural interdependence afforded by participatory CLD, urban factors were consistently prioritized in the representation of the integrated system, highlighting the need for new paradigms to support sustainable urban–rural transitions.

Keywords: causal loop diagrams; FEW nexus; urban–rural systems; 4P framework; sustainability; participatory modeling

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1. Introduction

Current developmental trends are leading to intense and growing pressures on natural resources, resulting in an increasing number of trade-offs and conflicts for all communities [1]. These dynamics can pose distinctive challenges in areas where large urban populations are adjacent to sparsely populated rural regions. Moreover, the interactions between these two regions and their dynamic and interrelated trajectories may respond to larger economic and demographic trends and the additional challenges of a changing climate rather than geographic proximity. Large urban centers tend to be more connected to other urban centers across the world than to the rural areas adjacent to them. Service and manufacturing sectors concentrated in cities create products designed for national and international customers. Cities are viewed as the primary drivers of global growth due to their concentrations of economic opportunity, but they are also drivers of inequitable, resource-inefficient, low-density growth and pollution [2–7]. Likewise, rural areas that produce fungible agricultural products and raw materials are highly connected to global commodities markets, and not necessarily to the closest urban centers. Even if, by chance, products are consumed locally, market prices respond to global supplies and demands. Thus, rural areas—like their urban counterparts—can be strong drivers of growth, but they can also cause decline when commodity prices slump, and commodity-driven production strains local natural systems. Urban life can be very different from rural life; consequently, this difference can lead to a political divide [8], which, in turn, is reflected in the separate spheres of urban and rural planning, each with their corresponding foci and biases [9]. Research may also be biased toward cities with respect to other pragmatic factors. Universities and researchers tend to be located in cities; thus, researchers study urban issues because they experience them. Funding agencies also tend to focus efforts on places where most people live. In contrast, rural planning is often the focus of other disciplines—ranging from agronomy to hydrology—rather than urban planning. Longstanding biases regarding urban planning and urban economics assume the value of rural areas lies in their potential to urbanize [10] rather than their support of urban function. Without rural areas, cities would not be able to survive.

The duality of urban and rural areas is also a false dichotomy. Even if their economic systems have few connections, they are inherently linked by shared natural (e.g., water, air, and climate) and human systems (e.g., transportation, policy, and political boundaries). Neither area is self-sufficient; they both need goods and services produced elsewhere. They face many of the same problems; inequality exists in both areas [4], and food deserts are not just inner-city phenomena [11]. Research needs to elevate rural concerns to the same level as urban concerns. Studies of urban–rural linkages that equally consider both regions can help create new insights about how to create a more sustainable future that is free from dependence on carbon-based energy sources and offers better environmental and socioeconomic outcomes. Urban and rural areas that cater more to each other rather than to distant markets will be more resilient to shocks, such as the breakdowns in transportation caused by COVID-19 lockdowns or food and energy shortages caused by the war in Ukraine.

The goal for our study was to investigate these urban–rural dynamics by focusing on internal and external stressors in socio-ecological systems [12], with particular attention paid to the food–energy–water (FEW) nexus, an essential component of the global agenda in 2011 [13], which was further supported and expanded in 2015 by the US National Science Foundation, the Belmont Forum, and other organizations [14,15]. There are other names for the FEW nexus that shuffle the order of the acronym, with the order often dependent on the expertise of particular researchers [16]; for example, hydrologists commonly refer to it is the WEF nexus and energy specialists as the EWF nexus [17,18]. Nonetheless, they refer to the same concept, wherein the three FEW components are closely integrated [19], and this connectedness seems to entreat the application of an interdisciplinary approach [20,21]. For example, water is necessary for almost all forms of energy production; energy is an indispensable component for water treatment and food distribution; and food production requires an uninterrupted supply of energy and water [22]. Furthermore, all these components have a significant impact on natural resources (e.g., water quality and supply, soil health, the nutritional value of food, and fuel production), as well as on pollution and greenhouse gas emissions. Each component of the FEW nexus is a complex and multi-component sub-system in itself, so analyzing them in conjunction adds significant complexity to their study and use so as to guide policy and implementation strategies. Due to their importance and inherent complexity, there is a need to understand how the components of the FEW nexus are structured in and across urban and rural areas to identify what current structures may impede these systems from adapting to and mitigating climate change, and tailoring solutions and approaches in each context [23]. argue that focusing on the nexus between FEW systems and spatial jurisdictions can help promote shared governance between regions and avoid the establishment and maintenance of siloed systems. However, Dodds [24] seems to suggest that a FEW approach can most benefit cities, but this too is evidence of a lack of understanding of the problems facing rural areas and why cities and rural areas are co-beneficiaries of this approach. Focusing on FEW integration equally in urban and rural areas can create more resilient systems and regions that experience fewer external shocks, whether caused by war, climate change, or diseases.

The understanding and planning of FEW systems offers special challenges and requires the pooling of expertise across multiple domains; in regions with urban and rural components, the knowledge needed must encompass both areas. Moreover, this level of understanding requires a combination of views and knowledge that must be intentionally created and fostered. We used a participatory modeling approach to create this opportunity, wherein our team worked with a diverse set of stakeholders with expertise in FEW domains to collaboratively create Causal Loop Diagrams (CLDs) connecting the various FEW factors within urban and rural environments to formulate relevant research and policy questions for in-depth exploration. Diverse groups of stakeholders will have a collection of knowledge exceeding that of any single expert, and with this pooled expertise they can collectively clarify the modeling questions, goals, decisions, and context. Participatory modeling involves a broad range of stakeholders—those who would be implementing changes suggested during the participatory process and those who might be affected by these changes—in the act of the modeling process. Although the use of participatory modeling is well established within the fields of natural resources management, its use has now grown much beyond these areas [25,26], particularly in urban and rural planning. The literature on this approach's use has found that it enhances the comprehension of complex problems through its structured learning framework [27] and leads to the more novel design and thorough exploration of possible solutions [28–31]. However, both planning and implementing the collaborative modeling process can be resource-intensive [26].

The complex, interconnected nature of this problem suggests that systems thinking and modeling represent a path forward. Systems thinking deals with the organization, dynamics, and logic of systems [32] and is beneficial for sustainability research [33–35] due to its recognition that socio-environmental components are embedded in complex systems [36]. Prior modeling efforts towards urban–rural linkages have included cellular automata, land use change models, and agent-based models, but tend to focus on the study of urbanization and its impacts, thereby perpetuating the biases outlined above. Another way to represent the complex structures we seek to study is through CLDs, which allow for visual inspection and other forms of analysis to identify key components that may have unexpected impacts due to feedback mechanisms within a system. CLDs stemmed from systems thinking or system dynamics in the 1950s [37–40]; they are used to map out the configuration of a system to understand its mechanisms and interactions. CLDs began to emerge in the 1970s as an abstract way to explore the role of feedback and reinforcing effects on a system [41], and to help organizations learn about a system's structures by explicitly mapping their complexity [39,42]. CLDs are particularly well suited for the study of sustainability [40,43]. CLDs are also more intuitive to non-modelers than computational or mathematical models of complex systems, thereby providing stronger support for the engagement of diverse stakeholders in collaborative model building and knowledge co-construction towards the formulation of management and policy questions, hypotheses, and insights.

In the following sections, we outline the steps we employed to conduct participatory modeling exercises with key stakeholders to collaboratively diagram a representation of this interconnected urban–rural system through FEW components. Our study area for the exercises was the Chicago, Illinois, USA, metropolitan area and the rural areas to the west. The structure of this paper follows the 4Ps framework proposed by Gray et al. [25] to report our experience in a standardized and replicable way that could be applied to other national or international contexts. We conclude this study with implications for research and policies concerning the urban–rural domain.

2. Materials and Methods

We have adapted the 4Ps framework from Gray et al. [25] to report our case study (described below). The four Ps of the framework correspond to: (1) the purpose, (2) partnerships, (3) processes, and (4) products related to our participatory modeling activity. Purpose relates to why stakeholders are involved and why the problem is being modeled, which help identify the project's goals. Process outlines how the modeling process is conducted, its scope, and its goals. Partnerships cover aspects of stakeholder involvement, their thoughtful selection based on domains of expertise, how relationships with them developed, and timing of their involvement. Products are the outcomes, both in terms of model-based products and social outcomes (e.g., learning, policy and management insights about the problem). In the following sections, we describe each of these components of the 4Ps framework in detail.

2.1. Case Study

Our study area is northeastern Illinois, USA, specifically, the Chicago metropolitan area, and its relationship with the rural areas directly west of the city. As a major air, rail, ground, and water transportation hub, Chicago has long been recognized as a global city, with strong connections to other areas of the US and the world. Its adjacent rural areas also serve a food market that extends well beyond Chicago.

Quantitatively, population densities in Cook County, where Chicago is located, can exceed 10,000 people per square mile, while in areas of Lee and Ogle County, less than 100 miles west, population densities fall to under 10 people per square mile in some areas [44,45]. Some common criteria define urban and rural territories, such as population size, density, the form of the built environment, and economic functions [12,46–48]. There is, however, considerable disagreement on the definition and delimitation of urban areas [12,49]. Our intention was not to establish a precise line dividing the urban and rural areas but to introduce in our discussions the urban–rural distinction with which most stakeholders are familiar. This plausible but not rigorous dividing line is situated approximately through Kane County, at a point where settlement density appears to the naked eye to drop starting from the area to the west of the settlements along the Fox River (see Figure 1). No further distinction was attempted. Intuitively, there is a clear distinction between the famous soaring skyscrapers of Chicago's downtown and the hundreds of thousands of acres of farmland found in counties to the west; we entered into our discussions with this simple distinction as our framing device.

2.2. Purpose

The purpose of this study was to explore and better understand connections between urban and rural areas within an FEW nexus framework. Dense urban areas and central business districts of large metropolitan areas are often assumed to constitute the most economically efficient form of living in human history [50], and to provide the best access to services and goods [51]. It is also frequently asserted that the corresponding density and productivity of urban areas represent the most environmentally sustainable form of living through which to reduce climate impacts [52]. Thus, rural areas are often viewed as fundamentally inferior to cities [53]. This leads to little understanding among people in urban areas of the lives and needs of people in rural areas, and vice versa, or of how these areas may interact.

The purpose of this participatory approach was to bring together domain and geographic experts that do not always interact to discuss these relationships. Stakeholders were involved in the project to consider opinions from both geographies. Our core team included researchers from various fields in social sciences and humanities. Through collaborative modeling, we sought to map out the interconnected urban–rural FEW sub-systems and identify the salient variables that may act as levers to create more sustainable integrated pathways. We expected that our external participants would also gain insights about these connections and apply them to their regular work. The overall purpose was further refined while carrying out the steps listed in the process section below (Section 2.4).

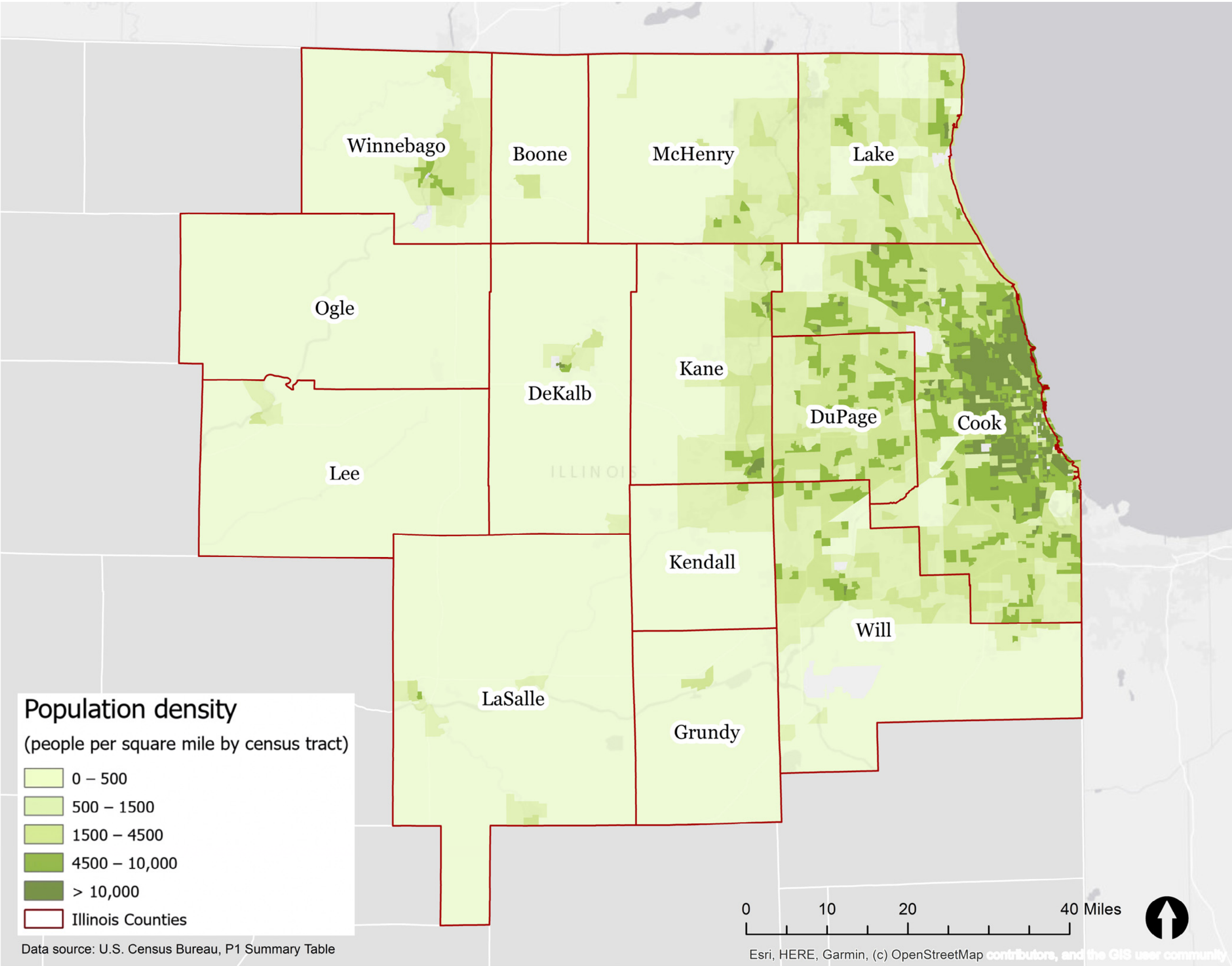


Figure 1. Population density in northeastern Illinois. Chicago is located in the eastern area of Cook County.

2.3. Partnerships

The partnership evolved through professional network contacts of the core research team and included academic, public sector, and non-profit partners with expertise in the FEW nexus domains in both urban and rural areas. Some participants also had expertise beyond the FEW nexus, such as in transportation, economics, and politics, which influenced the connections considered in the discussions. The participants work in a nearly equal mix of urban and rural locations (Table 1).

2.4. Process

We originally intended to have one all-day, in-person workshop to jointly search for unrecognized paths to sustainability in urban/rural interactions. However, the COVID-19 pandemic precluded this, and the team developed a new virtual strategy for holding smaller meetings, each focusing on one aspect of the FEW nexus, followed by a larger workshop to incorporate all sectoral diagrams into an integrated CLD.

Below, we describe the steps of the modified virtual approach (Figure 2), which follow a similar but distinct structure found in other studies focusing on childhood obesity [54,55], healthy eating [56], and corporate business indicators [57]. The sequence and combination of small- and large-group work were intended to foster knowledge cogeneration and support stakeholders' cross-validation of the e-system diagrams and insights derived from them.

Table 1. Overview of workshop participants: sector of work and area of expertise.

Geographic Focus	Area of Expertise	Sector	Years of Experience
Rural	Energy	Academia	20–30
Rural	Energy	Local government	30–40
Rural	Food	Academia	10–20
Rural	Agriculture/Food	Academia	20–30
Rural	Water	Public agency	20–30
Urban	Economics/FEW Nexus	Academia	10–20
Urban	Food	Academia	10–20
Urban	Food	Non-profit/private	20–30
Urban	Government	Academia	0–10
Urban	Water/Energy	Academia	20–30

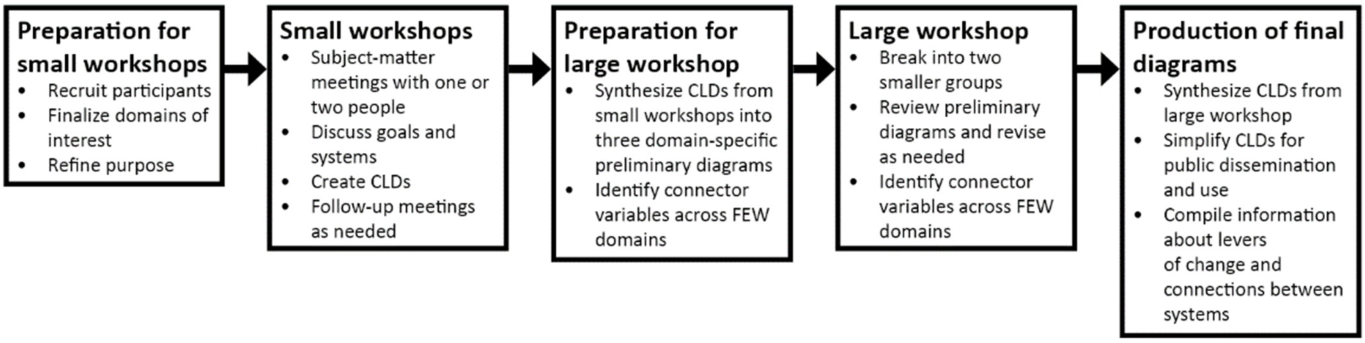


Figure 2. Overview of the process of the study.

2.4.1. Preparation for Workshops

The range of potential urban and rural interactions is very broad, and, initially, the research team contacted potential participants with expertise beyond the core areas of food–energy–water (FEW), but not all were able to join. Based on the domains of expertise represented, and to help fit the broad subject of sustainability to narrower topic, the core research team adjusted the focus to the FEW nexus and what is needed to restructure each of the three domains to create more resilient and equitable systems. During this phase, the core research team jointly crafted an initial CLD of the FEW nexus, which anticipated the kinds of discussions that might emerge during the various meetings with stakeholders.

2.4.2. Small Domain-Focused Workshops

Scheduling difficulties due to COVID-19 derailed our plans for a full-day, in-person workshop, pivoting to organize initial meetings with small subsets of our participant group around each specific FEW domain. These initial meetings lasted between 1 and 2 h. We held a total of 6 meetings, of which 2 were follow-ups to complete discussions and clarify questions (Table 2). Some of the participants had secondary expertise in a related field, which influenced the dialog greatly. For example, during an energy workshop, there was considerable discussion about transportation. There was one additional informal meeting with a potential participant with expertise in food systems, but they did not participate in the final workshop or help create any diagrams. Each meeting had one or two participants and at least two facilitators/members of the core research team present. Prior to the meetings, participants received a short video tutorial for Miro [1], an online platform for visual collaboration that supports dynamic whiteboarding and diagraming. In our meetings, we used Miro to jointly draw causal links connecting important factors in the FEW domain. We used either Zoom or Microsoft Teams to hold virtual, synchronous, participatory CLD workshops.

Table 2. Overview of workshops.

	Number of External Participants	Type of Workshop	Topics: FEW Domain
Workshop 1	2	Domain-focused	Water
Workshop 2	2	Domain-focused	Food
Workshop 3	1	Follow-up	Water
Workshop 4	2	Domain-focused	Food
Workshop 5	2	Domain-focused	Energy
Workshop 6	2	Follow-up	Food
Workshop 7	7	Synthesis workshop	Food, energy, and water

The first half of each workshop was dedicated to introductions, an overview of the project, and a general discussion about sustainability and the domain of expertise of the participant(s). We used Figure 3 to guide the discussion about the figurative divide between regions. The second half of the meeting was dedicated to the collaborative creation of CLDs. The team prepared a 'starter package' of materials with simple building blocks of variables, links, ideas for conversations, and an empty board. Participants could build on these starter packages or from a new topic within the domain that they felt was critical. The diagramming process involved typing the names of variables in virtual sticky notes and creating directional links that connected the variables. Positive (or direct) causal links (i.e., variables changing in the same direction) were colored black. Negative (or inverse) causal links (variables that change in opposite directions) were colored red. Uncertain causality was colored gray, and links that did not currently exist but could be created via a policy intervention were colored blue. Not all ideas or variables were integrated into the diagrams during the workshops, sometimes due to time constraints or uncertainty, but they were all video-recorded via the video-conferencing platform in use and added to the researchers' notes. Four preliminary CLDs emerged from these smaller workshops, which are shown in Figure 4 to highlight the system structures identified. Details on the variables and relationships are provided in Section 3.3.

Based on preliminary conversations within the research team and among the workshop participants, crucial variables for exploring urban and rural areas in the northeastern Illinois region in all three FEW systems were chosen. Those critical variables are supported by the literature and include water quality and quantity [58–60], economic development [61,62], urban [63] and rural [31] flooding, climate change [64,65], clean energy strategies [17,66], food consumption behavior [67], agriculture subsidies [68,69], and commodity and non-commodity crop production [70,71].

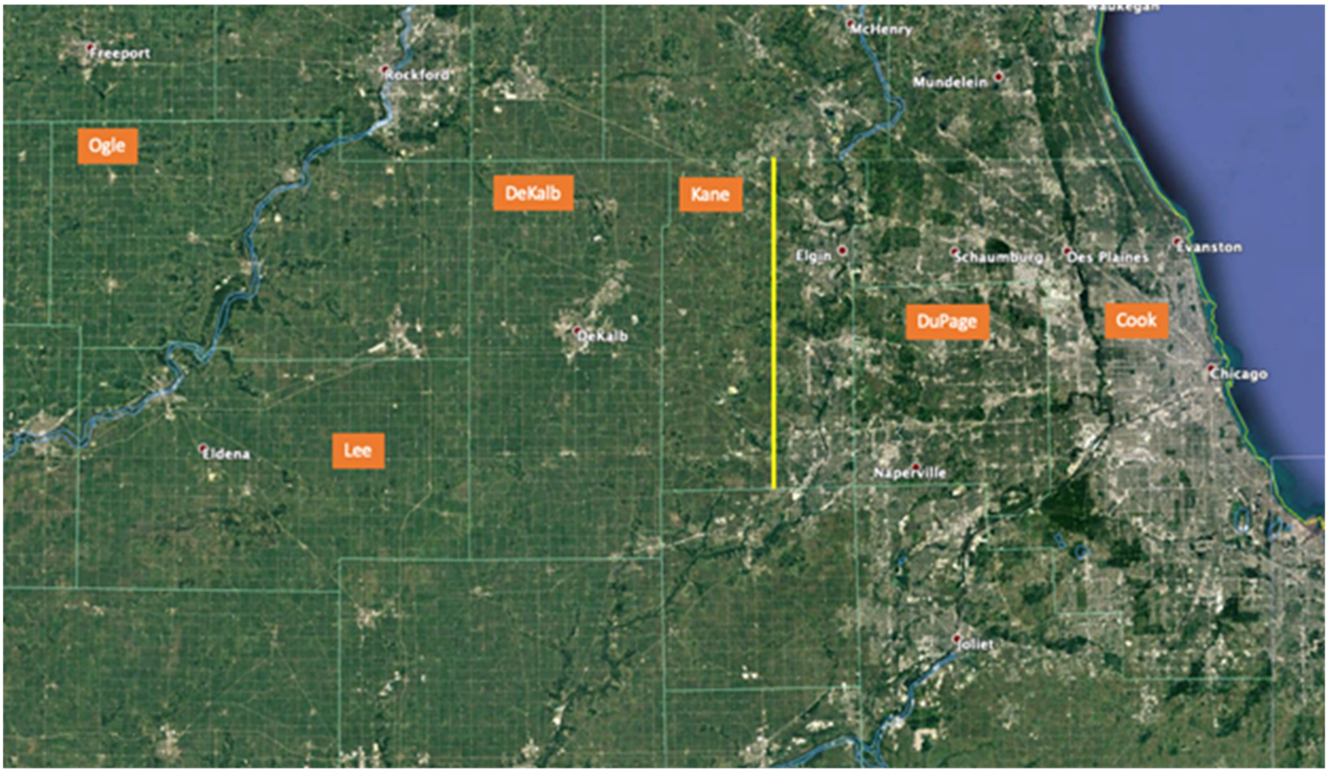
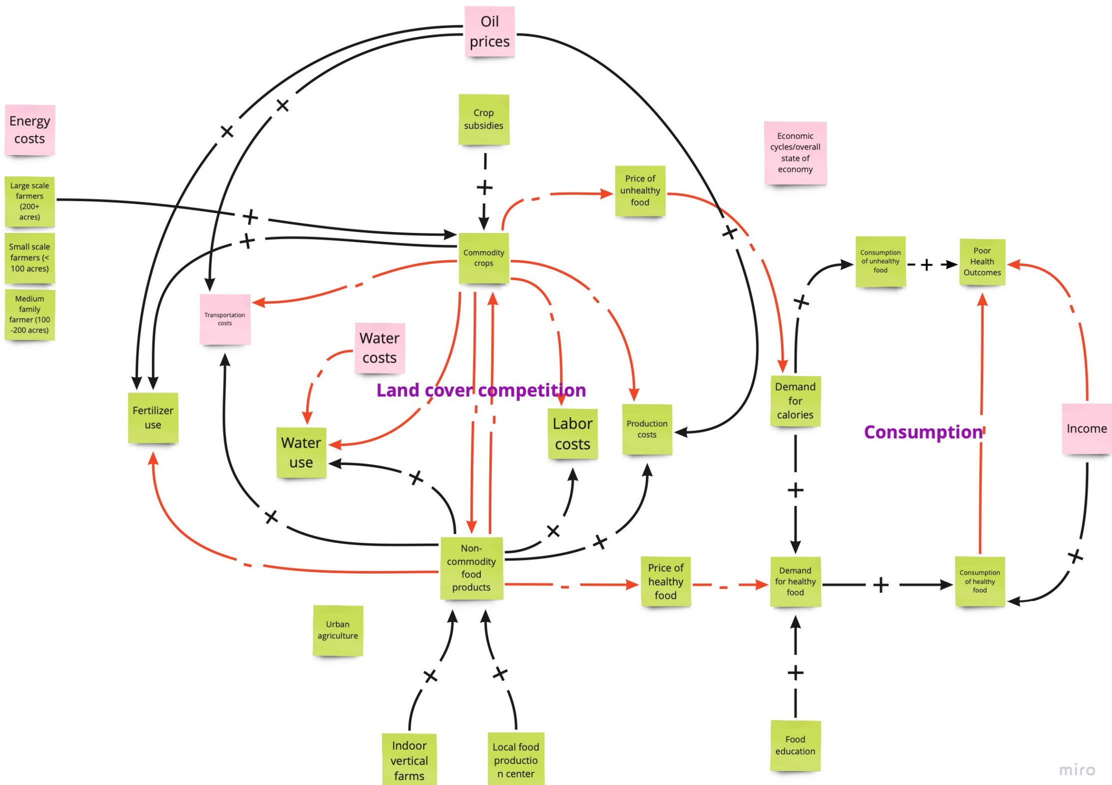
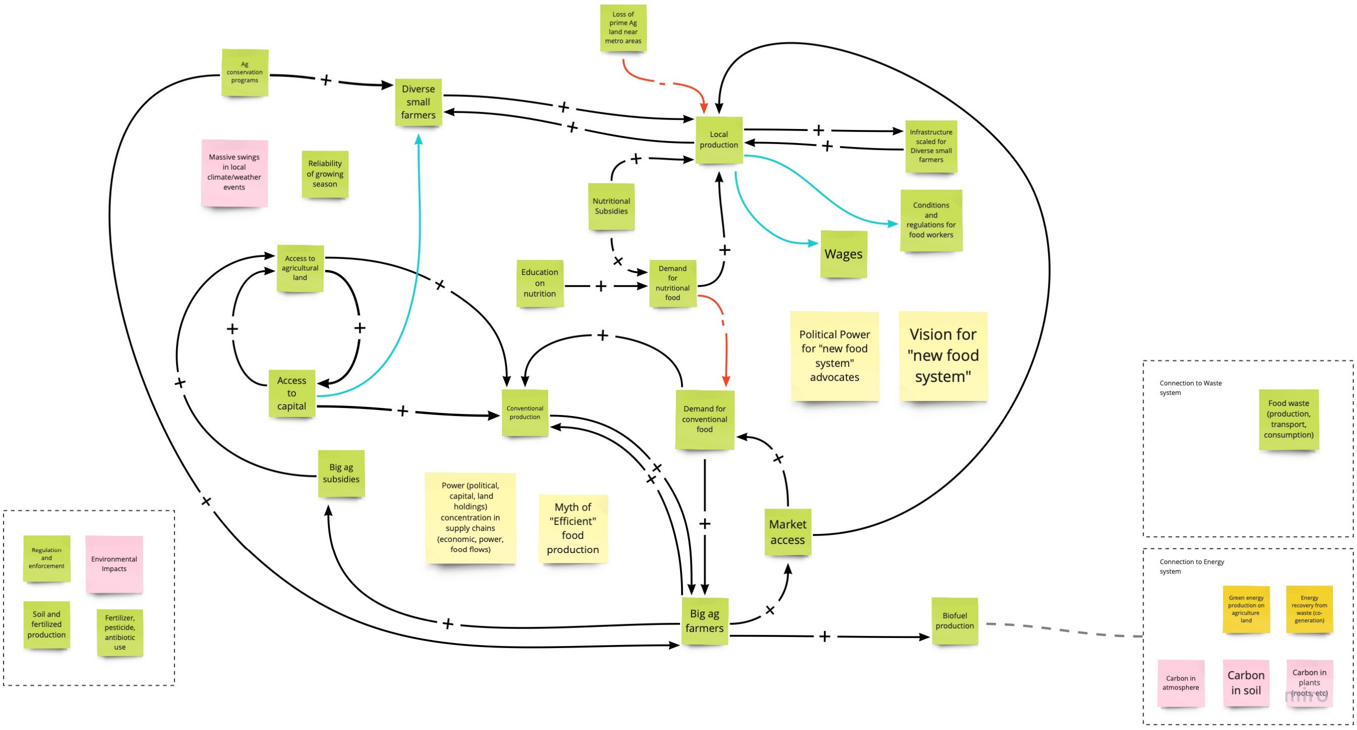


Figure 3. Satellite image of northeastern Illinois that was used in the workshops. This highlights one stark dividing line between rural (left of the yellow line) and urban (right of the line) areas (Source: Google Earth).



(**a**)

Figure 4. *Cont.*



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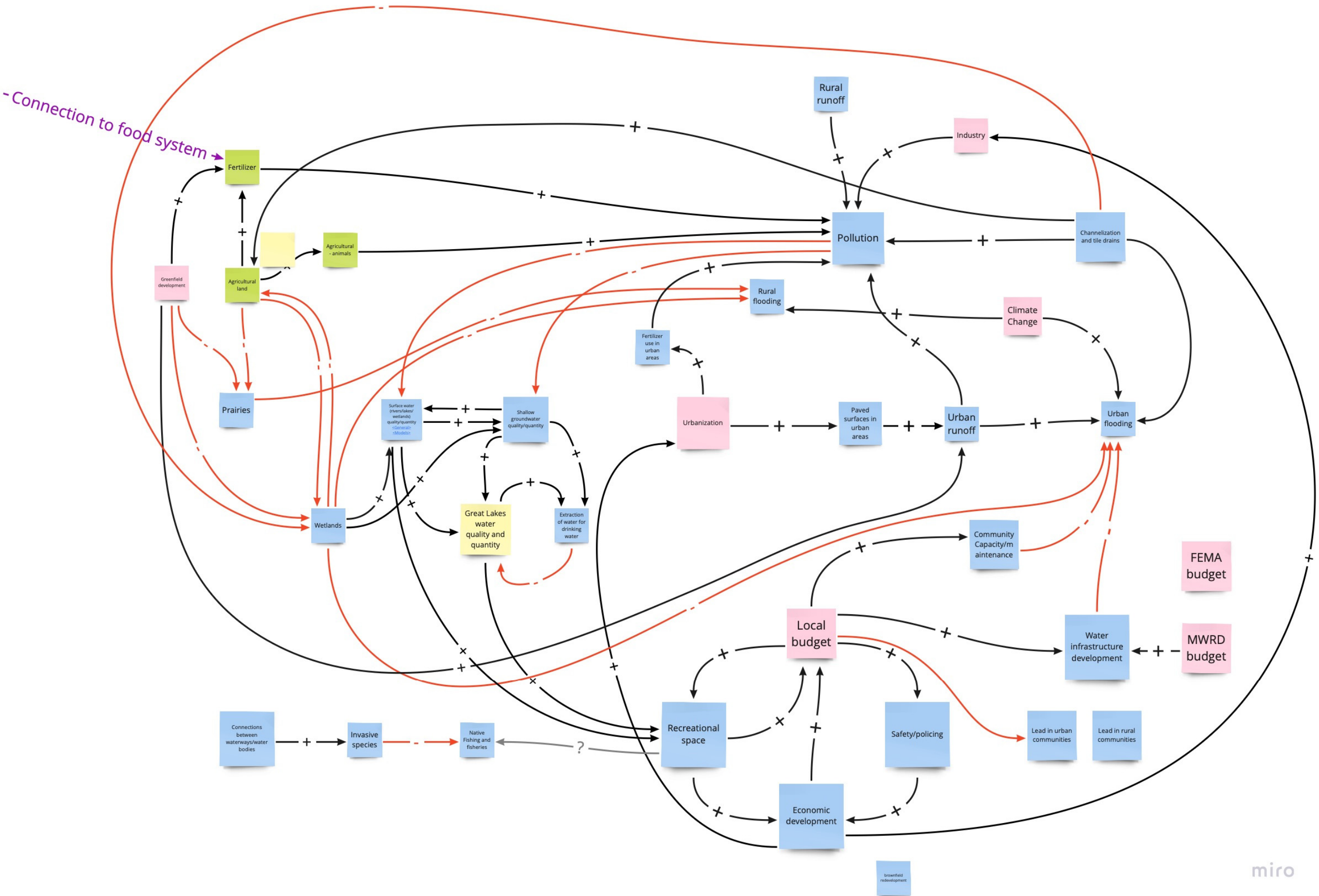
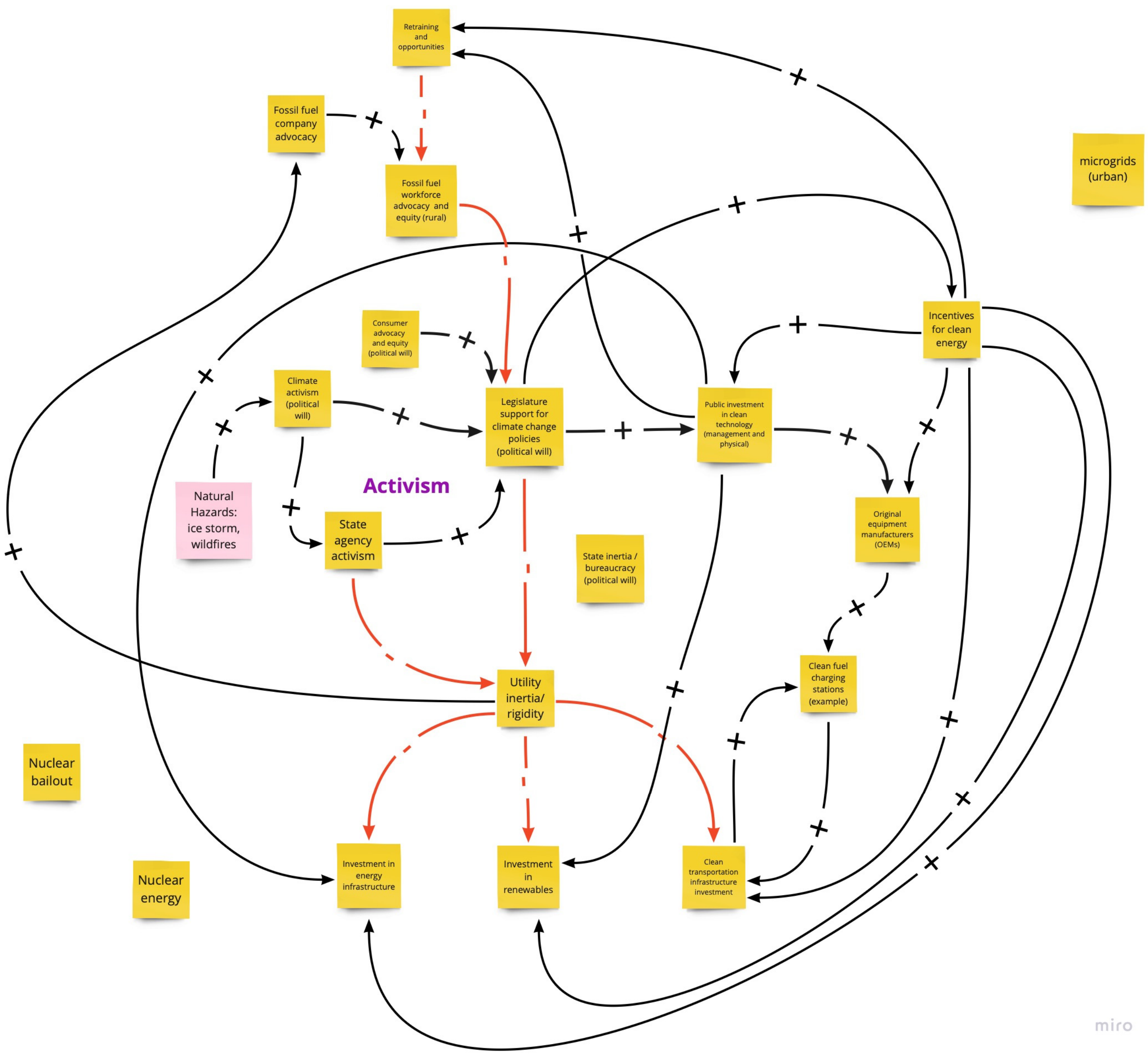


(c)

Figure 4. *Cont.*



(**d**)

Figure 4. CLDs from the preliminary workshops of food systems (**a**,**b**), water (**c**), and energy (**d**), created in domain-focused workshops. Black arrows show direct relationships; red arrows show inverse relationships. Green sticky notes denote food-related variables, orange sticky notes represent energy-related variables, and blue corresponds to water-related variables. Pink sticky notes denote exogenous variables. Yellow sticky notes represent tentative variables not yet finalized and integrated with the system. The smaller orange boxes are comments that participants added to the whiteboard. The names of specific loops are shown in purple.

2.4.3. Large Synthesis Workshop

After finishing all domain-focused workshops, our team began preparation for the final, large workshop and synthesized the diagrams from each meeting into a domain-focused CLD for each of the energy, water, and food systems. To enhance legibility, we labeled loops, eliminated duplicate variables, and spatially re-arranged variables on the board to reduce the crossover of links in accordance with good diagramming practice [40]; more detailed discussion of types of editorial changes is provided in the next section. Variables that connected across domains showed an open, purple, dashed link with text clarifying this cross-domain connection. We also highlighted variables that were mentioned as possible policy levers in domain-focused workshops. Each of these diagrams had at least one variable that had no connections to other variables due to uncertainty or time constraints, which were kept as placeholders for future consideration.

The next phase involved a 2 h workshop with nearly all the participants from the previous meetings (a few people could not attend due to scheduling conflicts). After introductions and instructions, participants met in two separate breakout groups, each including representatives of all FEW domains. Both groups had two facilitators from the research team. In addition, one member of the research team attended the two groups on an alternating basis to provide additional support and resolve any issues that arose. Of the five facilitators, two had extensive experience using CLDs in workshops, two had several years of experience modeling complex systems with other techniques, and one had less than a year of experience with complex systems. The research team spent some time discussing best practices for facilitation, and the more experienced facilitators were paired up with the more inexperienced ones. The main goal was to allow participants to discuss connections between the individual food, energy, and water domains and the potential for novel interventions for system-wide transformation [54,72].

The facilitators in each breakout group first reviewed the preliminary diagrams with the participants to confirm alignment with respect to their comprehension of the three domains. They proceeded to add or modify links and variables as needed. Finally, they collectively identified connections across the three dimensions, paying special attention to the rural–urban relationship and potential levers for change. We imposed few constraints. One such constraint was that we encouraged our participants to view climate change as an exogenous driver, and to resist drawing inward links to this variable. Our rationale for this was to ensure that the participants focused on local and concrete issues rather than global and abstract ones, and on short time scales rather than long ones. (For example, reducing emissions from our defined urban region in and around Chicago to zero, but assuming a business-as-usual status quo for the rest of the planet, would have virtually no impact on climate change as a driver in our system. In practice, our participants added inward links to 'climate change', showing that this was a salient narrative for them.)

2.4.4. Finalizing the Diagrams

The research team integrated the two sets of diagrams created by the two breakout groups during the synthesis process, making changes to improve clarity and comprehension while preserving their fundamental concepts and relationships. Table 3 below summarizes important connections between systems, key levers, new variables, and commonalities between both groups. This table guided the final synthesis of the diagrams by highlighting the most important findings.

To finalize our synthesis, we first revised variable names to render complex concepts domain-specific. For example, "biofuel production" became "land use for biofuel production" in the food domain to separate it from the energy domain and, in this way, highlighted the tradeoffs between fuel and food production. We shifted some variables to different domains where they fit better and renamed variables in multiple domains to differentiate the concepts, e.g., we reduced multiple variations related to fertilizer to just three to distinguish between its use in food production and its impacts on water quality. Some exogenous forces and sets of beliefs (e.g., the mindset that Illinois produces export commodities for global markets) were left without links to other variables due to their importance. However, others were refined and explicitly linked to other variables precisely because they were too generic. For example, "finite land supply", was captured through the tradeoffs between land uses, and "environmental impacts" was narrowed to runoff and flooding. Diagrams with fewer variables are easier to understand without additional guided descriptions.

Table 3. Summary of the final workshop: connections, levers, and new variables.

		Group A	Group B	In Common
Energy	Connections	– Climate activism in energy diagram is connected to the urban/local agriculture (food diagram)	– Land use in rural areas (e.g., cleaner energy, ag. Production); connection to energy and food – Methane and landfills: energy	– Importance of activism – Infrastructure for activism – New technologies – Connection between energy and water
	Levers	– New high-energy-consuming technologies: datacenters, mining farms	– Activism (consumers, pressure on policy makers) – Investments/incentives for infrastructure, technology (e.g., methane from landfills; 30 by 30)	
	New variables		– Infrastructure for activism – Profit incentive for cleaner policies	
Water	Connections	– Urbanization connected to: 1. Energy diagram. Changes (increase) in energy consumption 2. Food diagram. Urban Agriculture (non-commodity crops) 3. Within water diagram, to "Extraction of water for drinking water"	– Wastewater to energy – Hydropower to energy	– Wastewater treatment and energy – Costs for consumers as a lever
	Levers	– Levels of industry and other indicators are connected to broader issues of globalization, trade, etc.	– Activism for infrastructure – Politics – Pricing and rate structures – Actual scarcity of water in the analyzed location – Equity and justice (not represented in diagram) – Privatization (or water for all)	
	New variables	– "Wastewater treatment", which is connected to the energy diagram – "Residential water consumption", which is connected to costs (and energy diagram)	– Superfund – Hydropower – Wastewater treatment – Competition and Overfishing, treaties and fishing licenses	
	Other issues		– Tragedy of the commons (lead contamination, drinking water contamination, air pollution, drinking water supply, fishing)	

Table 3. *Cont.*

		Group A	Group B	In Common
Food	Connections	– "Large scale farmers (200+ acres)" to water ("Climate change") – "Overall water use" to water – "Food education" within food diagram to "Urban agriculture"	– Connected to energy: a. food production is energy-intensive b. wind farms can coexist with agriculture c. energy use of indoor agriculture	– Urban/indoor agriculture
	Levers	– Urbanization and Food education helps Urban agriculture	– Political power of agricultural companies – Crop subsidies – Animal feed – Elastic crop choices—relatively easy to switch between commodities – Reliability of growing seasons/natural disasters – Trade wars	
	New variables		– Energy use concerning indoor farming – Mindset that Illinois produces commodities for the whole world	

Changes to links went beyond what was necessary by revising the number and arrangement of variables (e.g., when a variable was removed, the links to it were also removed). To save time in workshops, linkages between domains were frequently left incomplete, wherein the name of the other domain was recorded rather than the name of the variable it should have been linked to. Later, we made explicit the connections between two variables in different systems. Thus, "land use for biofuel production" (in the food system) connects to "biofuel production" (in the energy system) rather than just to the energy system in general. In this case, the narrative derived from this link means that more biofuel production leads to more land used for biofuel production but less production of food crops.

The final step involved creating a set of simplified diagrams with sub-diagrams of closely related clusters of variables with a common theme to further reduce diagrams' size and increase clarity. We then shared these diagrams with external partners (workshop participants and others who had not attended the workshops). Examples of these new sub-diagrams include "clean transportation" and "investment in clean technologies" in the energy system, "development" and "fishing" in the water system, and "subsidies and economic power" and "urban farming" in the food system. In Miro, a user's display opens a sub-diagram by clicking on the corresponding high-level variable, thus making it easier to follow a narrative. Additionally, we omitted peripheral variables with few connections for thematic consistency. For example, we removed "nuclear power" because the focus of the energy diagram largely avoided traditional forms of power generation (e.g., no variables for coal or gas generation were included). Items that we excluded from being explicitly represented in either set of diagrams were still recorded in supplemental notes and tables.

3. Results

Gray et al. [25] describe three types of products for participatory modeling: modeling products (e.g., maps and diagrams), social outcomes (e.g., individual and group learning), and policy, management, and scientific knowledge (e.g., reports and policy options). Below, we synthesize the descriptions in the sections above, as they pertain to the various products of our process.

3.1. Modeling Products

The primary modeling product was the set of causal loop diagrams, whose development is described in Section 2.4. The final diagram (Figure 5) is intended for public dissemination and includes sub-models to enhance clarity. Additional modeling products are forthcoming as we perform quantitative analysis of the diagrams. Table 3 is itself a modeling product and guided the policy and managerial outcomes given below, i.e., the final product of this exercise (Section 3.3).

3.2. Social Outcomes

All the participants provided constructive comments about how the process was useful for them, i.e., providing them with insights regarding policy and practical directions that they had not previously considered. They expressed that they had learned about the systems through their involvement in them, and that they were able to think more broadly about how their own work relates to the work of others. For example, the connection between biosolids produced from wastewater treatment and soil regeneration prompted a discussion about the regulatory, market-related, and safety-related barriers that need to be addressed to allow for the flow of nutrients from food production to water treatment and back to soil regeneration in urban and nearby rural systems.

Following the synthesis procedure, we shared links to the simplified diagrams with all the participants, which allowed them to reference the work and main insights. Additionally, we produced a video summarizing the diagramming process and highlighting the major results. The video and a public-facing version of the diagram were made available to the participants and was published on the Internet [2]. We continue to follow up with the participants to maintain and grow a network that focuses on the paths to sustainability in integrated urban–rural areas. While many aspects of the diagrams are not strictly focused on rural–urban interactions, the generality of the diagrams enables their application in other contexts and research areas beyond our case study.

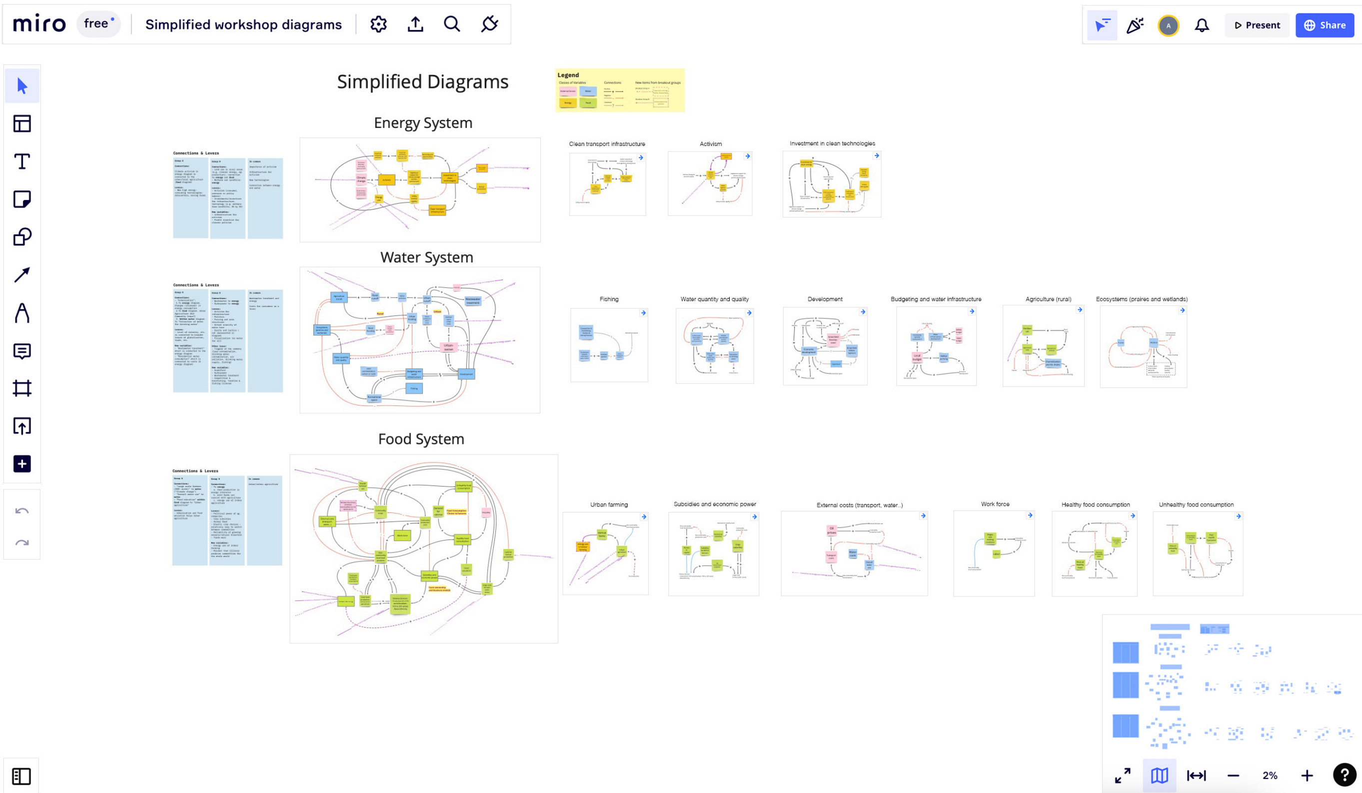


Figure 5. Depiction of the final product shared with workshop participants showing all three systems, sub-models, and information about connection and levers. This is provided for illustrative purposes only, so the text is not meant to be legible at this resolution.

3.3. Policy and Management Outcomes

We crafted narratives about problems in the domains and what types of variables might be policy levers based on the diagramming process and discussions with participants. These narratives describe where interventions should be focused in order to achieve high levels of impact that ripple through all three domains. We describe the most salient ones below.

3.3.1. Food Domain

Figure 6 shows the final, simplified version of the food diagram with three main foci: food production, consumption choice (healthy vs. unhealthy food), and the economics of farming (farm ownership, subsidies, and business models). The variables with blue arrows in their upper corner (e.g., "work force" or "subsidies and economic power") can be expanded in Miro to show greater detail of the associated sub-system. Although most of these relationships are extensively covered in the literature, the diagram underscores key tradeoffs, including the production of commodity vs. non-commodity crops, small farms vs. large farms [3], healthy vs. unhealthy food, and the ripple effects of existing policies, notably, the power of economic subsidies, which create a reinforcing loop of commodity production, large farmers, political clout, and continued support for subsidies. Thus, only two crops—corn and soybeans—cover 75% of the arable land in the Midwest [73], limiting the supply of local, fresh, and healthy foods [74,75].

Two narratives emerged that highlight the key levers with which to achieve a more sustainable food system. To weaken the pairing of large farms and subsidies for commodity crops (Figure 7), support for farmers who are Black, indigenous, and/or other people of color (BIPOC) can be implemented to promote diversity, not just in terms of race or ethnicity, but also with respect to the types of farms (i.e., more small-scale operations) that produce healthy foods with lower transportation costs and less food waste. Urban agriculture (Figure 8), the second greatest key lever, has a positive relationship with healthy, non-commodity food production; lower transportation costs; and greater urban self-reliance [76]. Although urban agriculture and vertical farming cause more fertilizer and energy use in cities, it results in an overall net decrease in these farming inputs for the entire northeastern Illinois region.

3.3.2. Water Domain

Figure 9 shows the simplified diagram for the water domain, which is visually organized by arranging the variables most salient to the rural area on the left, and those more saliently related to the urban area on the right. The rural portion highlights different types of natural systems (prairies, wetlands, and fish) and agricultural impacts, while the urban system is organized around urbanization, economic development, and wastewater treatment. The types of impacts (e.g., flooding, runoff, etc.) are often the same in both regions, but they manifest differently (e.g., different causes of flooding and water contamination). Balancing development and preserving natural systems is necessary to ensure that natural areas continue to provide ecosystem services that help buffer hazards (e.g., the detention and filtration of water, groundwater recharge, etc.) and that provide an engine for economic development (e.g., maintaining freshwater supplies for agriculture, industry, recreation, and human consumption) [73]. Participants noted how this domain, to a greater extent than the other two, presented numerous instances of the Tragedy of the Commons [77], leading to a game-theoretic question about payoff structures and games that could differ across urban and rural domains and be modified through policy.

Mapping these relationships revealed two key policy levers with which to increase resilience. Economic development has far-reaching effects on the capacity to manage flooding and provide water security [78] and this is seen in the sub-systems for budgeting and economic development (Figures 10 and 11). Recreational opportunities and economic development create virtuous cycles of increased financial resources, which, in turn, lead to the development of new water infrastructure and support infrastructure maintenance. However, development and urbanization coupled with policies that lead to greenfield development degrade natural systems, cause flooding, and impair water quality. Development must be undertaken in ways that preserve ecosystem services and recreational opportunities. An increased capacity to fund water-related infrastructure relates to another key policy lever: new technologies for wastewater treatment. Conventional wastewater treatment is extremely energy-intensive, but new approaches, such as improved anaerobic treatments, the capture of biogases, graywater recycling, and waste-to-energy cogeneration, are more efficient and can produce fertilizers as a valuable byproduct; thus, benefits can be spread to the energy and food systems.

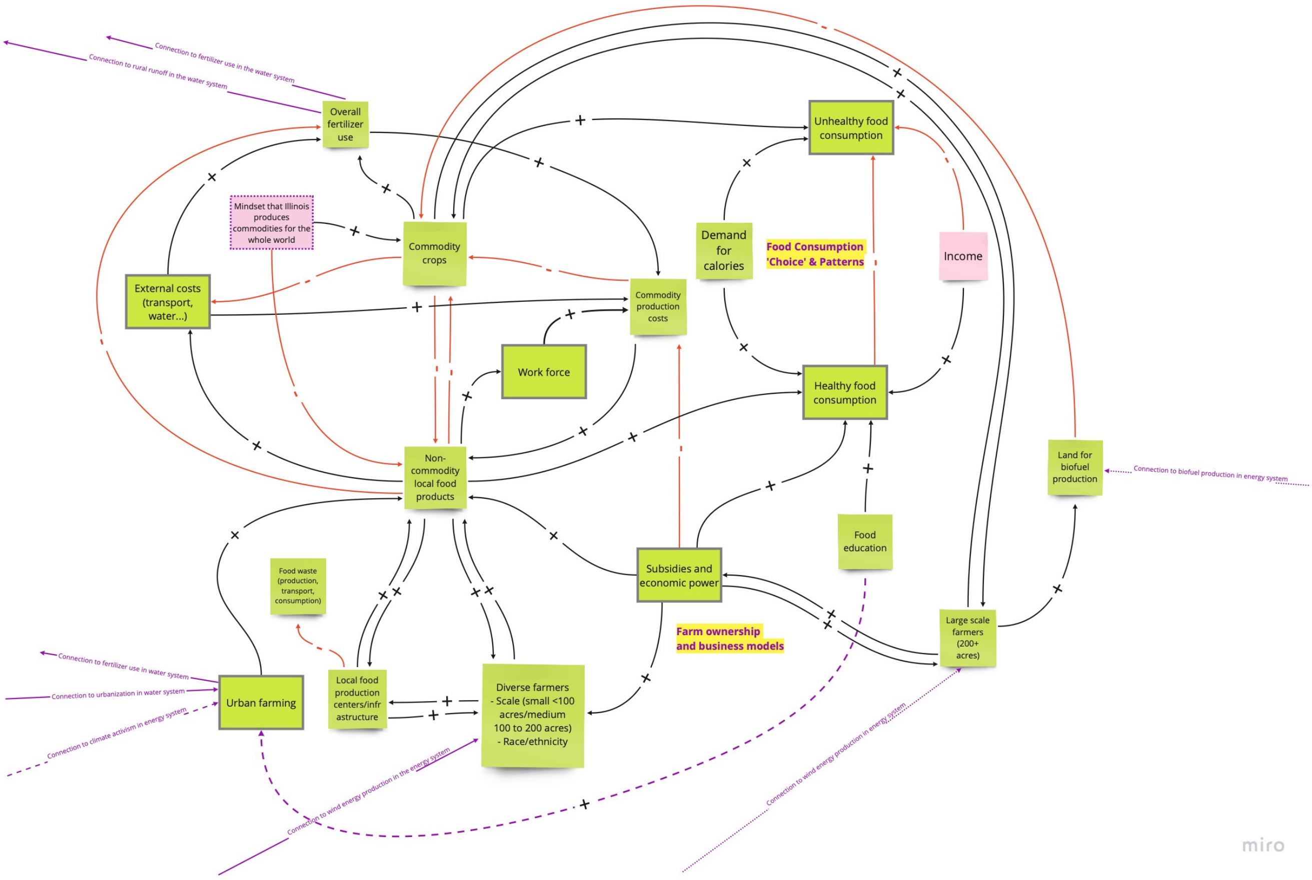


Figure 6. Simplified CLD of the food domain. Variables with a blue arrow in the upper-right corner point to sub-systems.

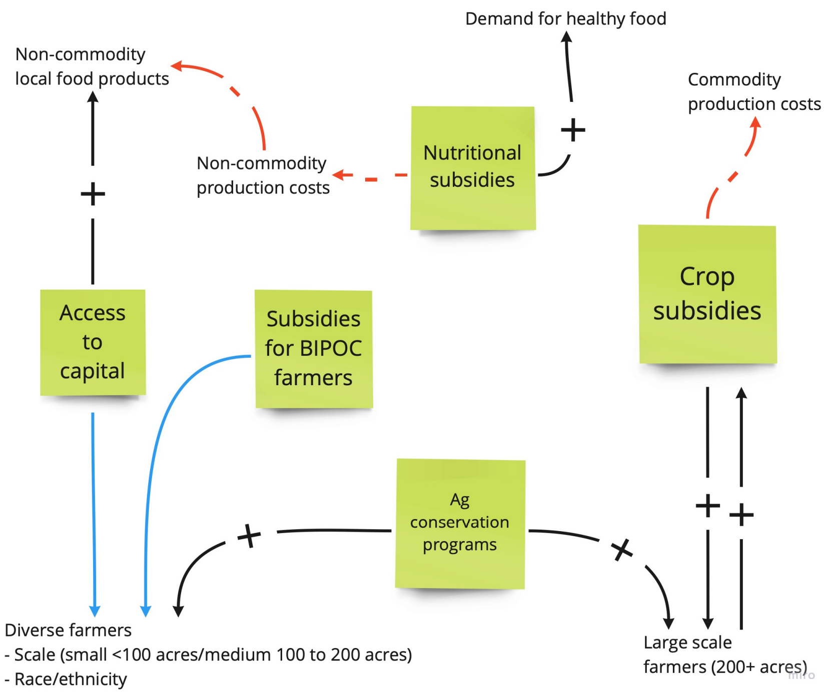


Figure 7. Subsidies and economic power subsystem.

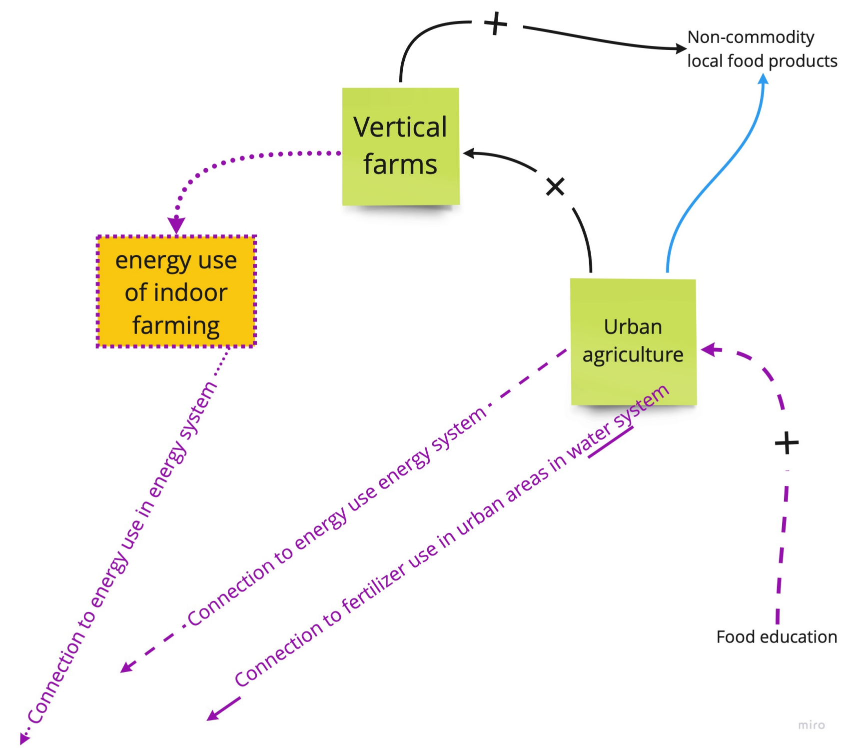


Figure 8. Urban farming subsystem.

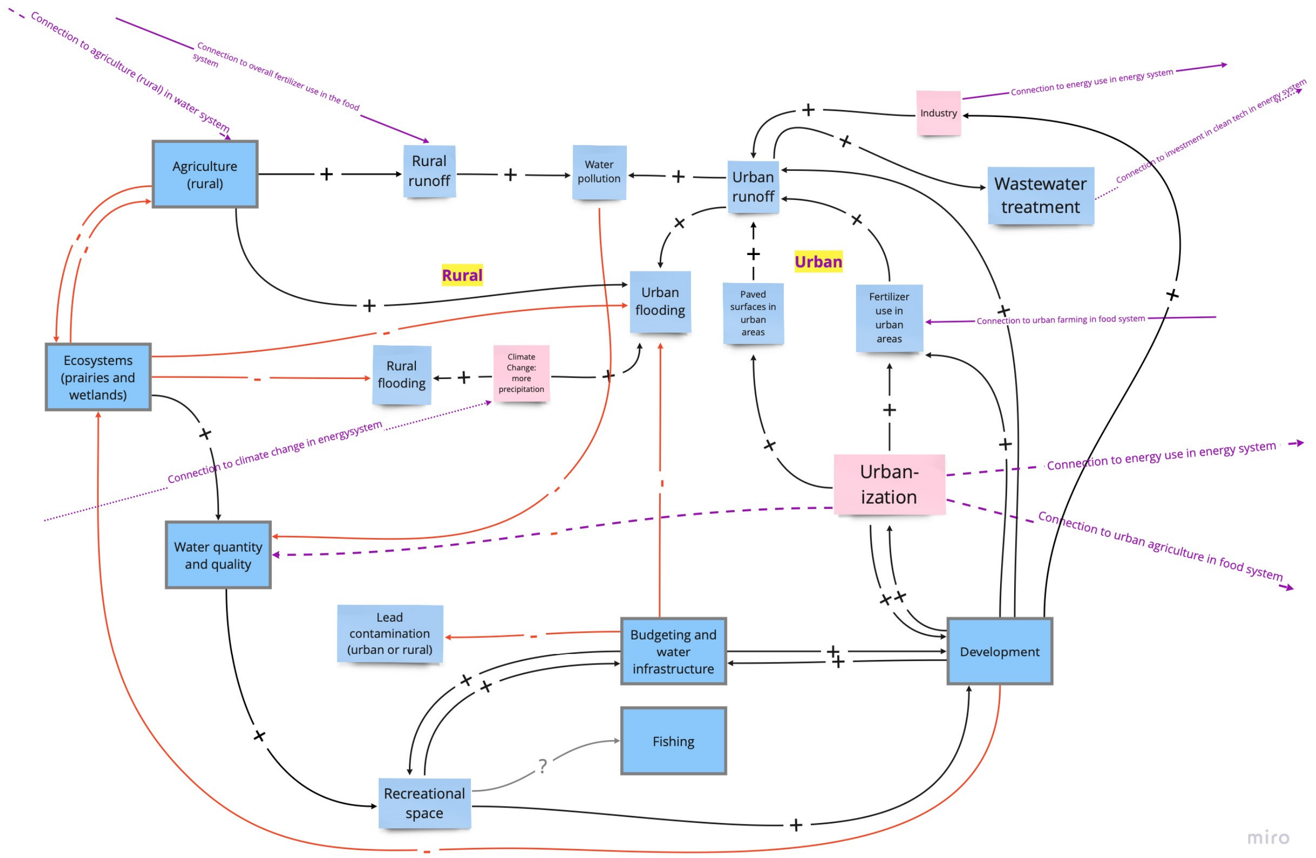


Figure 9. Simplified CLD of the water system, with rural relationships to the left and urban relationships to the right.

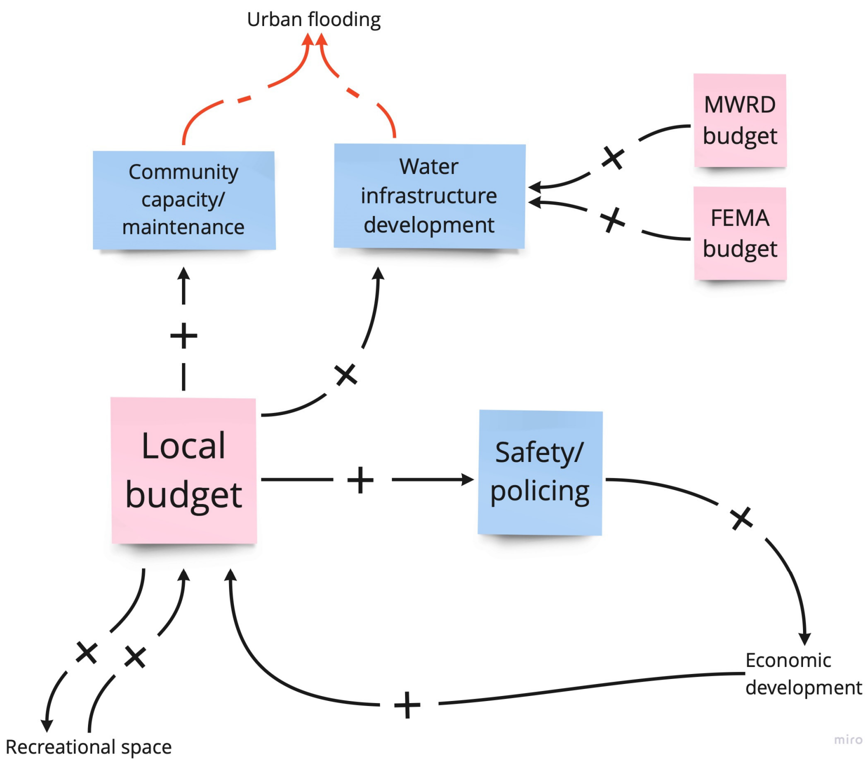


Figure 10. Budgeting and water infrastructure subsystem.

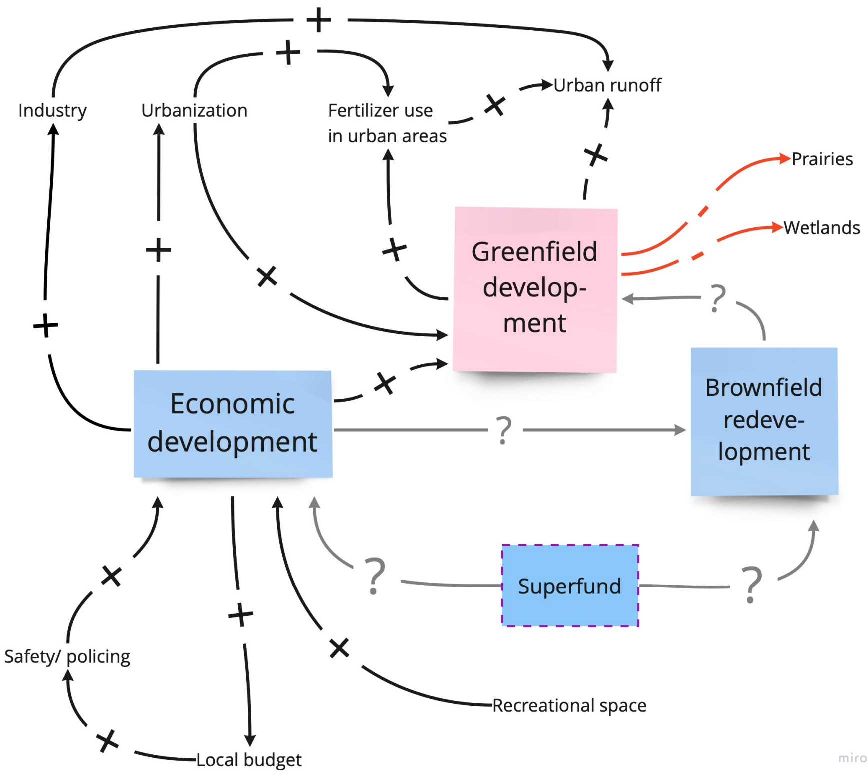


Figure 11. Urban development subsystem.

3.3.3. Energy Domain

Figure 12 shows a simplified diagram of the energy domain. Rather than focusing heavily on conventional issues of generation, transmission, or distribution, the participants concentrated on activism and the creation and adoption of new technologies, which are all levers for change within the broader energy domain.

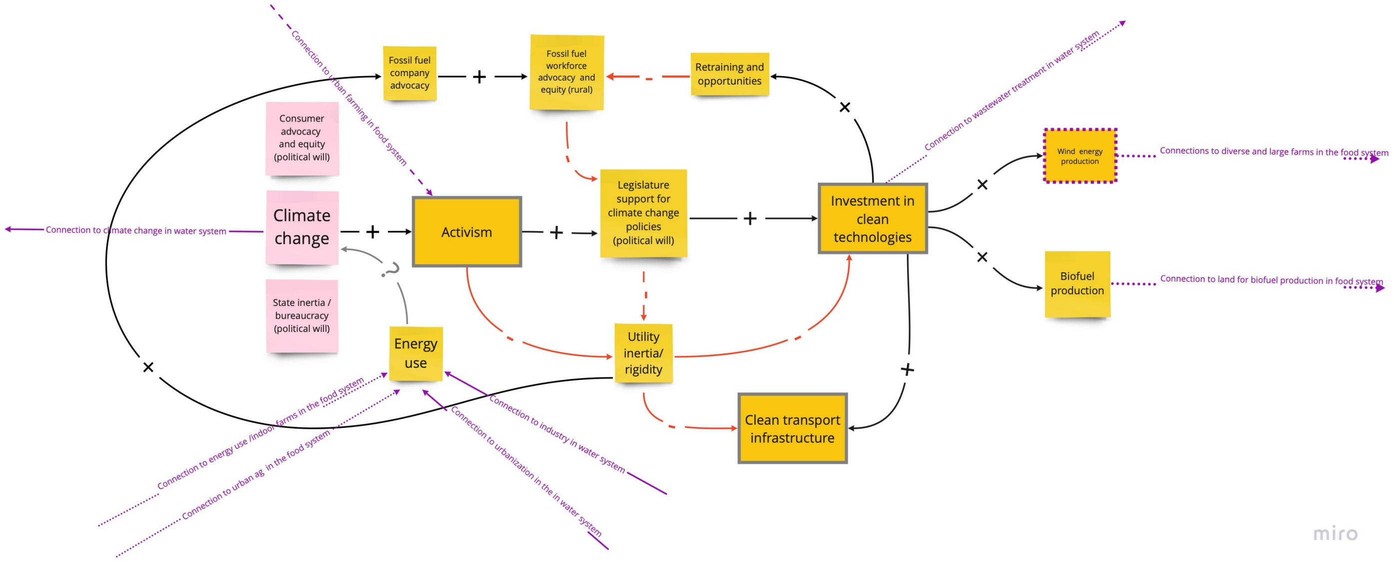


Figure 12. Simplified CLD of the energy domain.

Utilities are highly restricted in terms of what they can do, which is in part due to regulation, politics, and lobbying, but also because of the way that capital markets function, and what types of revenue streams are allowed. Activism—from school strikes to Earth Day demonstrations—generates media attention. Sustained activism creates social infrastructures (e.g., organizations and networks of activists) that help maintain and magnify these pressures. Figure 13 shows how the impacts of climate change drive the political will to make changes [79–81]. The workshop participants discussed how activism creates pressures not just on legislative bodies but on bureaucracies as well. Pressure applied from Illinois state bureaucracies to legislature can lead to policies capable of bringing tangible changes. Support for the development and implementation of new and cleaner technologies (Figure 14) can help counter the structural inertia of public utilities by incentivizing the associated parties' participation in realizing solutions. Examples of new, greener technologies and infrastructures that link back to the food and water domains include urban microgrids, green wastewater treatment, wind energy, and clean transport infrastructure. Transitioning from petroleum-powered vehicles requires significant public investments in transportation infrastructure (Figure 15), ranging from building electric-vehicle-charging stations to supporting original equipment manufacturers.

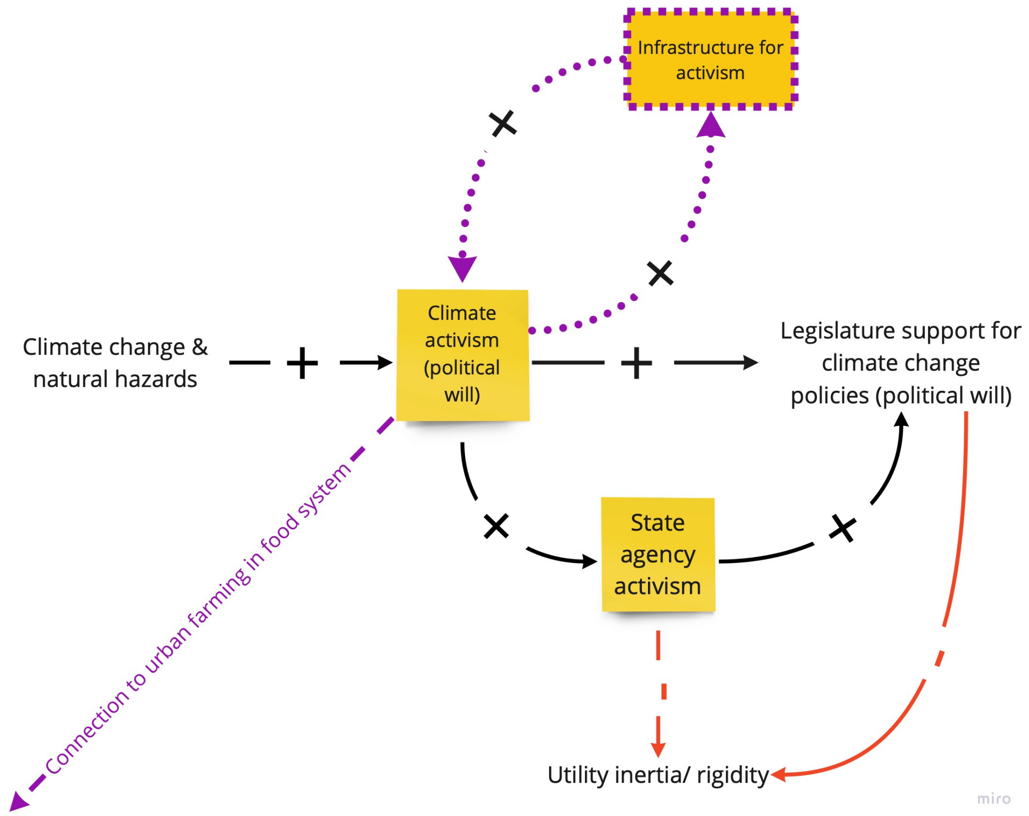


Figure 13. Activism subsystem.

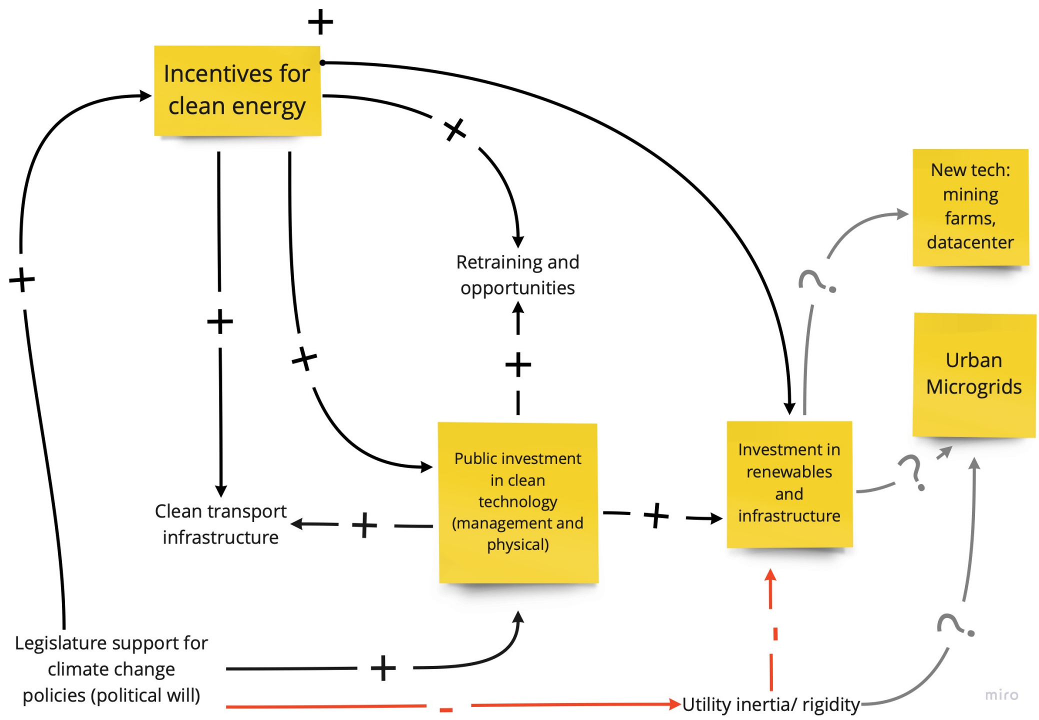


Figure 14. Clean technology investment subsystem.

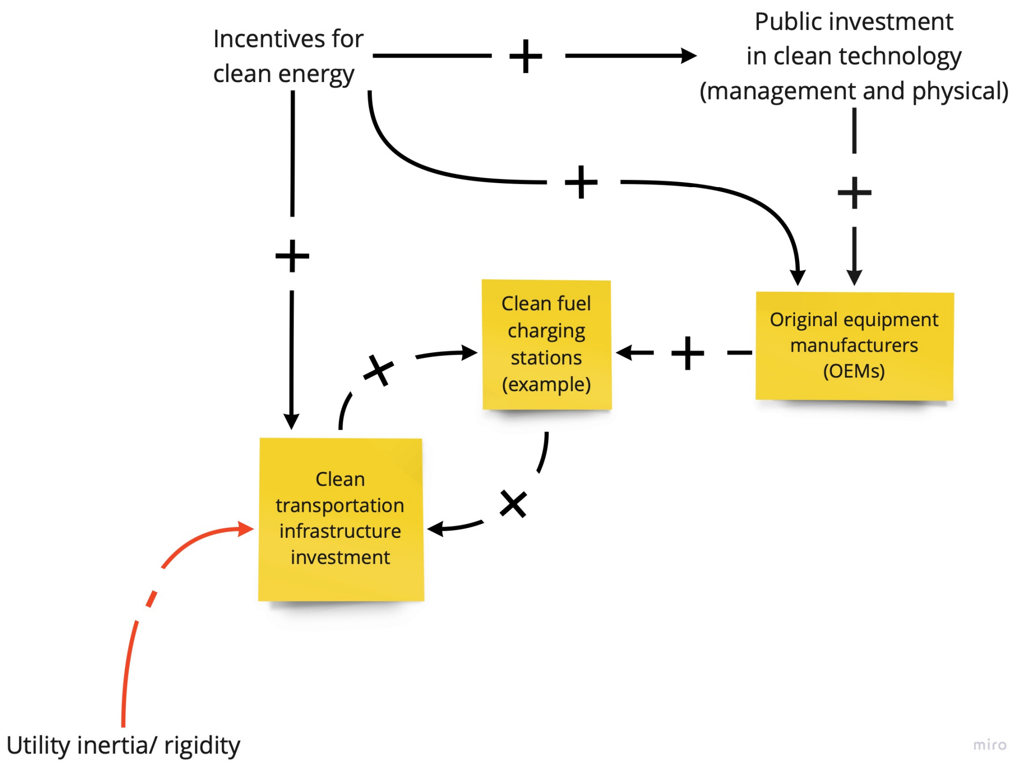


Figure 15. Clean transport infrastructure subsystem.

4. Discussion

We set out to explore questions and generate hypotheses concerning the barriers to and opportunities for sustainable transitions in integrated urban–rural systems within a FEW nexus framework. We implemented a participatory causal loop diagramming approach with key stakeholders who had domain knowledge of this system in northeast Illinois, USA. While the COVID-19 pandemic forced a transition away from in-person workshops, it gave us the opportunity to test a virtual strategy with which to scale up and facilitate broader engagement, to record discussions in workshops, and to document the evolving CLDs, whether they were edited synchronously or asynchronously.

An important outcome of this study's participatory modeling process is the development of a shared vision of the FEW nexus of integrated urban and rural areas in northeastern Illinois. Our participants' interactions not only provided their collective knowledge to our core research team but allowed for this knowledge to be shared among the participants as well. Our case showed how CLD is well suited to collaboratively organizing and representing complex systems in order to support comprehension of the FEW nexus and its connections within and across domains in urban–rural systems, anticipate the effects (intended or otherwise) of decisions within the system, and identify possible and novel levers for change to support policy design.

Several key policy insights emerged from the modeling process and discussions around it that contribute to the literature regarding urban–rural systems. The distortive power of agricultural subsidies over production in the food system is well known, but the process of diagramming indicated that support for BIPOC farmers can lead to enhanced food security and less waste. Urban agriculture and vertical farming emerged as other practices whose adoption can support the more sustainable production of nutritious foods in regions close to where they are consumed, with effects (both positive and negative) that reach the water and energy domains. In the water domain, economic development is the key force that provides resources and the capacity to invest in wastewater treatment technology that uses less power and provides organic fertilizer for both urban and rural agriculture. Nevertheless, new institutional, legal, and economic structures need to be created to support the closing of a vital loop with which to achieve soil restoration, as current economic and safety rules prevent a public wastewater treatment agency from selling biosolids. Additionally, economic development, if undertaken poorly, degrades the natural systems that facilitate prosperity. The impacts of climate change converge on the energy system, and activism is the essential lever with which to bring change, but this is true only if it can be sustained at high levels for long periods of time. The participants identified the possibility of joining forces with food advocacy organizations given their similar motivations, which could enable stronger influence across the system. Governments need to be pressured to create laws and regulations with which to support new approaches and receive buy-ins from powerful actors opposed to change. Policies need to tangibly support the implementation of greener technologies, including urban microgrids, green wastewater treatment, wind energy, and clean transport infrastructure, for transformational ripple effects through the entire FEW system, and in both urban and rural areas. A more in-depth quantitative analysis of the CLDs is underway to identify the nodes with greater potential for system-wide transformation. A comparative study of regions could even reveal that some of our insights are unique to Illinois, while others may be more generic to regions across the globe.

At this juncture, we return to the contention that urban areas tend to garner much more attention in the sustainability literature; less focus is applied to rural areas, and less still to the linkages between the two. The CLDs produced in this study highlighted some distinctions between how processes and impacts affect urban and rural areas differently (e.g., urban vs. rural flooding), but it is worth noting that these were few. While the distinction between urban and rural processes was repeatedly raised through our facilitation, the team of participants did not readily recognize it or highlight in the diagrams. Our specific interest in urban and rural linkages and their interactions was not the focus of any of the participants in their everyday work, and many of the discussions involved process-based (rather than geography-based) thinking around the regional FEW nexus in northeastern Illinois. It was also harder to engage collaborators focusing on rural areas than it was to engage those with urban priorities, thereby reinforcing the imbalance. While still yielding results that were productive and insightful regarding the implications for FEW nexus management, we were unable to counter the predominant biases towards urban areas.

The concept of urban–rural sustainability might have been too broad to be useful. Richer discussions, models, and insights might have emerged, with more focused and concrete goals and questions (e.g., how to ensure food security without perpetuating inequality or environmental degradation), especially around climate change. The time and resource constraints of the award that supported this work prevented the longer interaction needed to collaboratively define and refine the guiding questions.

Facilitation skills are critical for successful collaborative modeling efforts [26]. Except for the lead author, no other researchers in the team were very experienced in terms of facilitating such workshops, and the award constraints limited extensive training. The need to pivot to an online environment, while enabling us to move forward at a time when in-person meetings were not possible, compounded this limitation. In-person meetings would have allowed the lead author to "read" the whole room and provide support where and when it was needed, whereby insights and questions would be connected across groups. However, the use of breakout groups in a virtual setting made this impossible. Not all the participants were comfortable with the technology employed, which prevented them from engaging fully in the collaborative process, limited all parties' exposure to diverse ideas, and thus might have further contributed to the bias towards urban areas. Therefore, it is essential to design and provide facilitation training adapted to the unique demands of virtual settings, both to address the restrictions that a pandemic imposes on in-person meetings, but also because scaling up participatory modeling efforts to support sustainability transitions will likely require more extensive use of virtual spaces.

Our next steps involve continuing to refine the specific urban–rural focus that is central to our research project. Accordingly, we hope, with appropriate funding, to continue to work with our partners and expand our participant pool, thereby addressing the limitations that we outline above. The collection of data on the real-world magnitudes of the relationships proposed by our participants within our study area is also crucial in order to build on the CLDs and thus collaboratively develop computational models that can shed light on the dynamics and distribution of the socio-economic and environmental impacts of interventions in the integrated urban–rural system. A major focus of our future efforts will be to establish not only the existing linkages between urban and rural areas and how their dynamics play out in intended and unintended ways, but what beneficial linkages *could* exist that currently do not, i.e., the missed opportunities for a more sustainable and resilient future. Our diagrams constitute an initial effort in this direction.

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Conflicts of Interest: The authors declare no conflict of interest.

Notes

1. https://miro.com/ (accessed on 16 February 2023).
2. Northern Illinois University story: https://niutoday.info/2021/09/06/nius-urban-regional-modeling-helps-to-advance-environmental-research-and-policy/ (accessed on 16 February 2023). Public Miro board: https://miro.com/app/board/o9J_lDT6xtY=/ (accessed on 16 February 2023). Video: https://www.youtube.com/watch?v=ogvG9qDAg00 (accessed on 16 February 2023).
3. Our participants considered a large-scale farmer to be a farmer operating on an area of 200 acres and more; medium-scale farmer to be operating in 100-200 acres, and small-scale farmer, in less than 100 acres.

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