ORIGINAL PAPER

Resilience assessment of centralized and distributed food systems

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Abstract

Resilience, defined as the ability of a system to adapt in the presence of a disruptive event, has been of great interest with food systems for some time now. The goal of this research was to build understanding about resilient food systems that will withstand and recover from disruptions in a way that ensures a sufficient supply of food for all. In large, developed countries such as the USA and Canada, the food supply chain relies on a complex web of interconnected systems, such as water and energy systems, and food production and distribution are still very labor-intensive. Thanks to economies of scale and effective use of limited resources, potential cost savings support a push towards a more centralized system. However, distributed systems tend to be more resilient. Although distributed production systems may not be economically justifiable than centralized ones, they may provide a more resilient alternative. This study focused on the supply-side aspects of the food system and the food system's water, energy, and workforce disruptions to be considered for the resilience assessment for the USA, with an example for the state of Texas. After the degree of centralization (DoC) was calculated, the resilience of a food system was measured. Next, the relationship between labor intensity and production of six major food groups was formulated. The example for Texas showed that the decentralization of food systems will improve their resilience in responding to energy and water disruptions. A 40 percent reduction in water supply could decrease the food system performance by 28%. A negative correlation was found between the resilience and DoC for energy disruption scenarios. A 40 percent reduction in energy supply could decrease the food system performance by 34%. In contrast, achieving a more resilient food system in responding to labor shortage supports a push towards a more centralized system the decentralization of food systems can in fact, improve their resilience in responding to disruptions in the energy and water inputs. In contrast, achieving a more resilient food system in responding to labor shortage supports a push towards a more centralized system.

Keywords Resilience · Centralized systems · Distributed systems · Food-Energy-water nexus

1 Introduction

The disruptions triggered by COVID-19 have demonstrated how vulnerable our food system is, even with numerous interventions made during this pandemic to ensure people continue to have an adequate supply of safe food. Food security is a major global challenge. Everybody needs food, and because of their essential role, food and agriculture create jobs and enhance the economy. A resilient food system is able to withstand and recover from disruptions in a way that ensures a sufficient supply of acceptable and accessible food for all. Many large, developed countries such as Canada and the United States (US) follow a centralized food system, in which production is concentrated within a small number of large farms and plants and food products are distributed over a wide area. In contrast, distributed production systems may provide a more resilient alternative as they make supply chains less vulnerable to disruption. For example, when five major meat packing and processing plants in the US shut their doors during the COVID-19 outbreaks, over 80% of the beef and 60% of the pork production in the US were disrupted. Perhaps a solution is to return to a de-centralized system where end users found their food supplies from local

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and regional producers. The purpose of this study is to assess whether decentralization affects the resilience of a food system when exposed to stresses and shocks.

A recent study by the authors (Karan & Asgari, 2021) revealed that consistent conclusions or insights on resilience cannot emerge from research on food systems alone. The literature has consistently found food insecurity to be negatively associated with health and economy (see Gundersen & Ziliak, 2015). Aside from the economic and nutritional consequences of food insecurity, better food access can reduce terrorism activities since various dimensions of food insecurity are closely associated with terrorism and armed conflicts (Adelaja et al., 2018). A recent study estimates that a 1-kilocalorie increase in the depth of food deficit would decrease the incidence of civil conflict by 2.4 percent (Mary & Mishra, 2019). These are just a few reasons why more attention on factors affecting household food security is warranted. Achieving food security has two obvious solutions. First, we can take steps to help prevent disruptions (e.g., climate threats and water scarcity) of food production or distribution. Second, we can build more resilient food systems to ensure a sufficient supply of acceptable and accessible food. Since major natural disasters and extreme weather events are not preventable, we can reduce their impacts with the help of a more resilient system (second solution). Therefore, the focus of this study is to understand the impacts of disruptive events on the food system and how sectors beyond food may influence the resilience of a food system.

In a general sense, a system is a collection of interconnected or interacting entities that are organized toward a common goal. Similarly, as a social-ecological system, a food system is a group of interrelated activities involving the production of food, and its processing, packaging, and transportation to feed a population (Ericksen, 2008). In systems theory, one of the major characteristics of systems is that they have inputs and outputs (Delchamps, 2012). These food production units include the large-scale commercial farms as well as the small-scale, smallholder farms, with their large labor force, their crop diversity, the frequent inclusion of livestock in agriculture, and their limited reliance on external inputs (Savary et al., 2020). The first stage for building resilience of food systems during and post COVID-19 pandemic involves understanding the present condition of the food sector with respect to food procurement, storage, processing, and consumption (Priyadarshini & Purushothaman, 2021). We will better understand how food systems can be properly prepared to withstand and recover from disruption or crisis by answering the following questions:

1. What and how much essential outputs must the food system produce to meet human nutritional needs?
2. Which activities are involved in producing these outputs?

3. What and how much inputs are necessary for these activities to produce the desired outputs?

2 Global and US food systems

Food systems exist at different scales: global, regional, national and local. Local food systems around the world are very diverse and location specific (von Braun et al., 2021). In contrast, global food systems are diverse and complex, involving everything from subsistence farming to multinational food companies. In large, developed countries such as the USA and Canada, the food supply chain relies on a complex web of interconnected systems, such as water and energy systems, and food production and distribution are still very labor-intensive. Despite their difference, food systems operate on economies of scale to increase overall production and maximize efficiency to reduce consumer costs. Understanding the US food system explores the fundamentals of agricultural production, food supply chain, and human nutrition that will guide us through the issues that shape our food system. Because of economies of scale and effective use of limited resources, potential cost savings support a push towards a more centralized system. Although distributed production systems may not be economically justifiable compared to centralized ones, they may provide a more resilient alternative. This situation invites a discussion and research about choosing distributed production systems for food production instead of centralized systems. We do not know whether decentralization contributes to resilience.

Over the past century, the US food system radically transformed from one sustained by local farms to an industrialized system dependent on agricultural practices and advanced food processing operations. Such a centralized system often further elongates the distance between food sources and consumers. Although the scope of the paper is focused on the US food system, the failures and the promise of this complex system can be a model for the world. The dietary and nutrition guidelines, such as the eating patterns and nutritional limits recommended by the U.S. Department of Agriculture (USDA), can be used to determine the food system outputs. We use the recommended combination of six major food groups including vegetables, fruits, grains, dairy, protein foods, and oils (USDA, 2015) as the essential outputs for the food system. Table 1 lists each food group's recommended amounts for a moderately active household consisting of one male and one female adult, 36 to 40 years old, and a child, 10 years old. The data are developed for the average male and female adults and children in the U.S.; for adults, the reference male is 178 cm tall and weighs 89.7 kg who needs 2,600 cal per day, and the reference woman is 162 cm tall and weighs 77.3 kg who needs 2,000 cal per

Table 1 Recommended intake amounts for an average U.S. household

Category	Consumption (kg per week)
Vegetables	9.5
Fruits	6.2
Grains	3.6
Dairy	12.5
Protein Foods	3.0
Oils	0.5

day (Fryar et al., 2018). For children, the reference boy or girl is 142 cm tall and weighs 38.5 kg, who needs 1,800 cal per day. With an average household size of 2.6 people in the U.S., only 60 percent of a child's consumption is considered for the calculation of the total household consumption. The number of calories needed for an average U.S. household is estimated to be 39,760 cal/wk (or 5,680 cal/day).

This paper focused on the supply-side aspects of the food system, and thus, the activities involved are planting, producing, harvesting, processing, packaging, and transporting. Each activity relies on a variety of resources. Figure 1 shows an overview of the food supply chain and the relevant inputs/resources. Natural resources, labor, and capital are three categories of resources or inputs used to produce outputs. Examples of natural resources required for food production and distribution are land, water, energy, and minerals. Examples of capital inputs are buildings, equipment, chemicals for processing, materials for packaging, and technology. This category of input heavily influences the use of human and natural resources. For instance, smart irrigation systems (e.g., evapotranspiration controllers) would lead to an average irrigation reduction of 20 percent compared to scheduled irrigation systems (Masseroni et al., 2020). Livestock and dairy farms with automated feeders and robotic milking machines would produce more with less labor. While some of the activities involved in food production and distribution may not require substantial amounts of energy or physical efforts, both energy and labor are essential inputs for transforming food from field to fork. It is expected that the results of this paper provide an extra dimension to our understanding of the food complex and layered system. It is expected

to provide an improved assessment tool to gauge resilience by clustering food systems based on their architecture (e.g., centralized systems at one end of the spectrum and distributed systems at the other end of the spectrum).

3 Background

Since its introduction by Holling (1973), the concept of resilience has evolved considerably in the context of socio-ecological systems. Generally, the resilience of a system is defined as the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks (Walker et al., 2004). In the context of food systems, Tendall et al. (2015) defined food system resilience as "the capacity over time of a food system and its units at multiple levels, to provide sufficient, appropriate and accessible food to all, in the face of various and even unforeseen disturbances." There are many other definitions for food system resilience, including one provided by Hoddinott (2014) that defined the food system resilience as the capacity that ensures adverse stressors and shocks do not have long-lasting adverse development consequences. We use the Tendall et al. (2015) definition as it connects resilience to a functional goal.

Resilience thinking can potentially contribute to the security and sustainability of food systems (Naylor, 2009). Previous studies have applied resilience concepts to specific contexts or specific stages of the food supply chain. For instance, Pingali et al. (2005) explored relationships between food security and crisis in different contexts in order to draw the policy and institutional conditions. King (2008) examined how agroecological systems using community development processes can make communities more sustainable and resilient. The Food and Agriculture Organization (FAO) of the United Nations (U.N.) (Alinovi et al., 2008, 2009) estimated household food resilience to unpredictable shocks using statistical methods in the case of Palestinian households. Alinovi et al. (2010) empirically measured the results of different livelihood strategies with regard to household resilience to food insecurity in the case

Fig. 1 Overview of the activities and inputs involved in the food supply chain
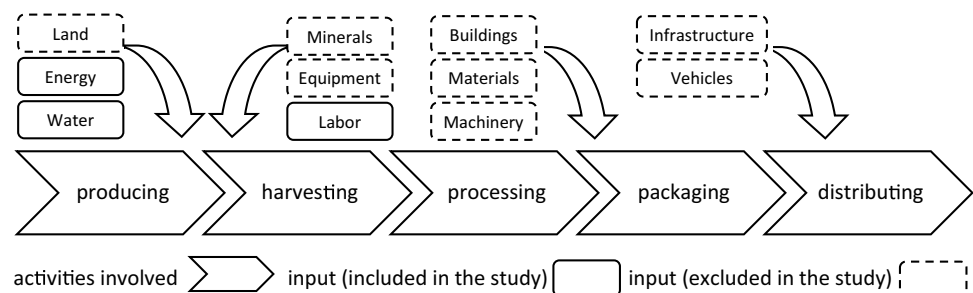
of Kenyan households. Milestad et al. (2010) investigated how local food systems can improve resilience through exploring the learning potential among farmers and customers. Van Apeldoorn et al. (2011) analyzed the agroecosystem using five existing key heuristics of the resilience perspective. Allouche (2011) investigated water and food systems' resilience and sustainability to disturbances associated with a range of factors including war/conflict, economic crisis, and climate change.

A series of studies presented in the 2012 joint FAO/OECD workshop reviewed conceptual frameworks for climate change-related vulnerability and investigated and discussed the resilience of agriculture, forestry, and fisheries (FAO/OECD, 2012). Among these, Babu and Blom (2014) outlined the main capacity components of a resilient food system and proposed a systematic method for investment prioritization of capacity building strategies. LeBlanc et al. (2014) used qualitative methods to analyze the development of nonprofit food hubs in Vermont, USA, and recommended building resilience strategies. Bizikova et al. (2016) introduced a systems-based framework for food security and applied it to evaluate the food system resilience of 20 communities in Honduras and Nicaragua in the context of climate change. Lamine (2015) suggested a territorial agri-food systems perspective that considers the diverse actors, institutions, and relations in and between agriculture, food, and the environment. Paci-Green and Berardi (2015) studied the case of western Washington, USA, and suggested a food resilience strategy based on regional farm production. Manning et al. (2016) developed a business resilience risk assessment framework for determining an organization's strategic resilience in the food supply chain. Pelletier et al. (2016) studied the vulnerability of rural livelihoods in international cases and provided practical challenges to assessing resilience in various contexts. Toth et al. (Toth et al., 2016) developed a qualitative tool for analyzing food resilience in the context of urban environments. Zimmerman et al. (2016) used a network model to quantify interdependencies among food, energy, and water (FEW) systems in terms of resource usage, not food resilience. Pathmanathan et al. (2017) identified the technological, institutional, organizational, and infrastructural shortcomings due to war and provided recommendations for building a resilient food system in the postwar context in Sri Lanka.

Other literature investigated practical recommendations for resilience improvement. Worstell and Green (2017), for example, proposed the common qualities of resilient food systems and compare them with those proposed in the literature in order to establish quantitative indicators and later form a sustainability/resilience index. They assumed resilience as a function of connectivity, local self-organization, innovation, maintenance/redundancy, accumulation of value-added infrastructure, transformation, ecological integration,

and diversity. In his recent work, Worstell (2020) used the COVID-19 crisis to examine how these eight qualities are exemplified. Zeuli and Nijhuis (2017) analyzed the urban food system resilience of five major American cities in face of natural disasters, climate change, social upheavals, and economic shocks and provided practical recommendations for resilience planning. Spies (2018) examined the impact of transformations of livelihoods and farming systems on the food system resilience in northern Pakistan's mountain communities. Jacobi et al. (2018) used the three resilience dimensions (buffer capacity, self-organization, and capacity for learning and adaptation) defined by Carpenter et al. (2001) and defined specific indicators for each dimension in order to operationalize the concept of resilience. They applied these indicators to different food systems (agroindustrial, local, and agroecological) in Kenya and Bolivia and identified contributing and undermining trends as well as potentials for building resilience.

To the best of our knowledge, previous studies focused on selected components of food systems and did not take into account either the level of centralization (or decentralization) of food systems or water, energy, and labor as main food system inputs and their impact on the resilience of food systems. Research on these aspects is needed because the resilience analysis frameworks developed or proposed over the past few years failed to quantitatively evaluate the resilience of a food system to a specific disruptive circumstance such as labor shortage. The preventive actions vary for each disruptive event so the applicability of broad or not specified resilience assessments seem very limited. To assess the effectiveness of various resilience interventions (e.g., decentralization of the system), one must understand the factors that impact resilience, as well as the definitions of the system performance. Consequently, we do not know whether decentralization contributes to resilience. The existing methods can be used generically on a wide variety of systems and under different disruptive scenarios. The problem is that previous studies face challenges in assessing system behaviors to a specific disruptive event because their metrics have not precisely defined around system performance.

4 Scope and research question

Following from this background, this study was intended to assess the current state of resilience for the food system. A resilient food system is defined as a system that can withstand a major disruption within acceptable degradation parameters and return to normal or improved operations within an acceptable time. Some disruptive events (e.g., pandemics and natural disasters) create a host of human and natural resources problems. Thus, key inputs of labor, energy, and water were the major focus in this study. Other

inputs such as land and capital resources can also influence the resilience of the food system, but were not included in this paper. The next section elaborates on the labor intensity and water and energy-use requirements of the food systems.

There are two spectrums toward food system topology; In centralized food production systems, the food processing plant is at the center of the process and the produced food is distributed through a network of stores and restaurants to multiple end-users. In contrast, distributed systems produce and supply food on a small scale and are spread out over a wide area. Most systems ended up somewhere in the middle of the spectrum. Prevailing research to increase resilience often suggested to change system topology (e.g., decentralized and interconnected systems are significantly less vulnerable to single-point failures). Coupled with the impacts of intensifying climate change, countries, states, cities, and communities are acknowledging that a more decentralized food system architecture comprised of distributed food resources—such as such as greenhouses, dual crop farming, fish farming, and microgreen farming—is safer and more resilient in a rapidly changing political and environmental context (Abdullah et al., 2021). In order to frame this discussion, our study sought to answer the following research question:

4.1 Does decentralization of food systems improve their resilience? If so, to what extent?

The following steps should be taken to answer that research question:

1. Decentralization should be quantified so that we can compare two food systems based on their degree of centralization (DoC). That step is explained later in this section.
2. The resilience assessment considers a single performance measure. It is necessary to describe the way we measure the system performance. If we use the recommended food intakes as the essential outputs for food systems, then we can measure the food system's performance level as the number of households or people with sufficient food access.
3. When assessing system resilience for specific disruptions, we should determine the labor intensity, water and energy requirements of the systems and then analyze the impact of labor, energy, or water disruptions on the food system. This task is explained in the following section.
4. A common basis is needed to draw an analogy between performance, water, energy, and labor. The cost of these different inputs/outputs are measured on a common basis of money so we use the cost of labor, energy, and water to determine the food cost. Knowing the household cost

of food (called food budget) and the household income, we determine how many households have access to sufficient food and determine the system's performance level for different DoC.

We determined the DoC to address the research question effectively. In a centralized food system, all consumers are connected to a central production unit that supplies and distributes the food through links. On the contrary, a distributed food system involves farms (production units) and distribution centers that are geographically dispersed and generally positioned close to customers. Therefore, the food systems with few production units have a higher degree of centralization. In contrast, if consumers are closer to where the food is produced, the food systems have a higher DoC. The DoC can be expressed mathematically as follows:

$$DoC = \frac{NoC}{NoP} \times \frac{\sum_{i=1}^{NoC} (C_i \times D_i)}{\sum_{i=1}^{NoC} C_i} \qquad (1)$$

where NoC is the total number of consumers, NoP is the total number of production units, C is the food demand per consumer, and D is the distance between the production unit and its consumers.

Figure 2 shows how to calculate the degree of centralization. In this example, the food systems produce foods for seven consumers (NoC = 7) with a total demand of 37 (e.g., 37 t), thus $\sum_{i=1}^{7} C_i = 6 + 4 + 9 + 2 + 5 + 3 + 8 = 37$. The left system shows a centralized system with one production unit (NoP = 1), while the one on the right shows a distributed system with two production units (NoP = 2). The degree of centralization for these two systems can be calculated as:

$$DoC_{left} = \frac{7}{1} \times \frac{(6 \times 14 + 4 \times 21 + \cdots + 8 \times 18)}{37} = \frac{7}{1} \times \frac{668}{37} = 126.4$$

$$DoC_{right} = \frac{7}{2} \times \frac{(6 \times 10 + 4 \times 13 + \cdots + 8 \times 16)}{37} = \frac{7}{2} \times \frac{531}{37} = 50.2$$

This mathematical representation makes the comparison of food systems regarding their degree of centralization possible. For example, we can conclude that the food system shown on the left side of Fig. 2 is around 2.5 times (126.4/50.2) more centralized than the system shown on the right.

We need a common basis to draw an analogy between different concepts of resilience. Usually, the cost of different inputs, outputs, and resilience improvements are measured on a common basis: as money. Thus, we estimate all elements of this study's monetary value to perform subsequent analysis in a single-attribute matter. For example, every food production system can have its own locally generated biomass feedstocks. Biomass fuels from agricultural crops and waste materials can easily absorb disruptive events' impacts

Fig. 2 Centralized (left) and distributed (right) food systems
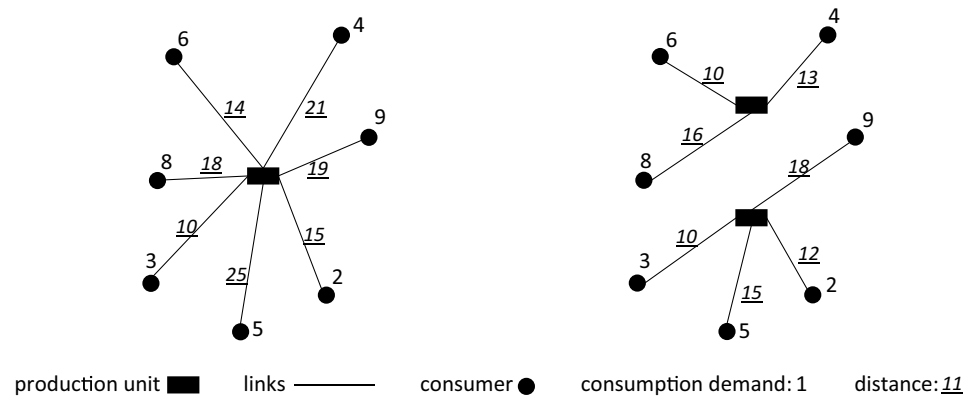
and minimize consequences with little effort. Furthermore, biomass is an organic material and thus a renewable source of energy. It may provide us a resilient and sustainable solution, but we should keep in mind that the average cost of electricity generation from biomass could be 40 percent more than that for a natural gas-fired combustion turbine. It may appear that food systems receiving their electricity needs from a combustion turbine plant are less sustainable and resilient at first, but using less expensive energy sources can contribute to invest in actions to maintain or increase assets (buffer capacity) and potentially improve resilience.

To analyze the impact of labor, energy, or water disruptions on the food system, we should first determine the labor intensity, and water and energy requirements of the food systems. The next section represents the labor, energy, and water inputs of the food systems based on a common basis, money.

5 Energy and water requirements for food systems

This study aimed to measure the food system's ability to perform its goal (i.e., meet human nutritional needs) in the presence of energy or water disruption. This goal requires an understanding of the differences in energy or water access

by the food system. Access to energy or water is related to the distance of energy or water sources from the demand point such as a food production unit. The ease of access to a resource is reflected in its price; in general, easier (closer) access would result in lower prices. We express the differences in energy and water access in terms of money. Access to energy and water can be quantified based on the available budget. The household diet quality is consistently associated with household income (French et al., 2019). The budget share for total food in the U.S. has changed little during the last 20 years and Americans spent an average of 10 percent of their disposable personal incomes on food (USDA, 2019a, b). Accessible energy or water input can be calculated as follows:

$$Input_{E \text{ or } W} = \frac{Budget}{\left(FC + VC \times D_{E \text{ or } W}\right)} \tag{2}$$

where FC is the fixed cost of water or energy (e.g., US$3 per 3785.4 Liter of water or 12 cents per kWh of energy), VC is the variable cost of water or energy (e.g., $0.3 per 3785.4 Liter per 160.9 km or 2 cents per kWh per 1609.3 km), and D is the distance between the production unit and the input source.

Table 2 shows the water and energy requirements for all six food groups and the inputs required for an average U.S. household. The water data is compiled from Mekonnen and

Table 2 Water and energy inputs to meet the food demand of an average household in USA

Category	Water footprint (L per kg)	Energy footprint (Wh per kg)	Water requirement (L per day)	Energy requirement (KWh per day)
Vegetables	322.1	661.1	438.3	899.7
Fruits	962.2	1419.3	854.3	1260.0
Grains	1644	1722.2	863	904.0
Dairy	1019.8	758.3	1830.6	1361.3
Protein Foods	7802.9	1111.1	3438.2	489.6
Oils	2364.2	1147.2	183.9	89.2

Hoekstra (2010) and the energy data are adopted from Ladha-Sabur et al. (2019). A food system requires around 7,608 L of water and 5 MWh energy per day to produce enough food to meet the nutritional needs of an average U.S. household. Knowing a complete enumeration of the population or the number of households, the energy and water inputs can then be calculated. By taking into account the fixed and variable costs of water or energy, we can use Eq. 2 to calculate the budget needed to achieve the food system output.

In measuring the system resilience for centralized and distributed systems, we rely upon the assumption that the same budget and capital resources are available to both systems. Today continuously rising freight costs often call for a distributed food system for closer proximity with the customers. Transportation or shipping costs could contribute considerable benefits to distributed systems and thus should not be ignored. The shipping rates are regulated by a myriad of factors such as weights and the origin to destination distance (the longer the distance, the higher the shipping rate). The transportation cost can be incorporated into the energy budget because all modes of transportation rely on energy (petroleum products or electricity). Therefore, the transport cost should be subtracted from the energy budget and then we can calculate the accessible energy input.

The scope of the resilience offered here is mainly based on "absorptive capacity", that is defined as the capacity to which a food system can absorb the impacts of system disruption (Francis & Bekera, 2014). The resilience metric can be generally defined as the ratio between the performance level immediately post-disruption and before any recovery efforts (P_D) to the expected stable performance level (P_0) and calculated using the following equations:

$$\text{Resilience} = \frac{P_D}{P_0} = \frac{\sum_{i=1}^{N} \frac{min(Threshold\ Income\ and\ household\ Income)}{Threshold\ Income}}{N} \quad (3)$$

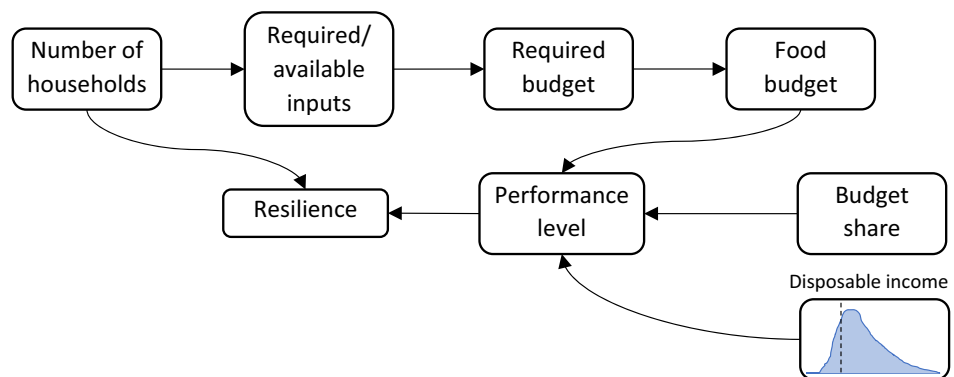$$Threshold\ Income = \frac{Budget_{food}}{budget\ share}$$

$$Budget_{food} = \frac{min(avail.\ inputs\ and\ req.\ inputs) \times (FC + VC \times D)}{share\ of\ inputs}$$

where N is the total number of households (could be equal to NoC is Eq. 1), $Budget_{food}$ is the food budget, other parameters are adopted from Eq. 2).

Figure 3 shows the process of measuring a food system's resilience to a disruptive event (e.g., insufficient labor, water, or energy supply). The right to food is a human right so the expected stable performance should be the total number of households or people. A food system's performance level is defined by the number of households or people with sufficient access to food There is no doubt that a disruptive event itself can be a threat to food security (e.g., people affected by COVID-19), but the consequence of the loss of income and purchasing power induced by the disruption can be more damaging than the actual disruption (Béné, 2020). When we calculate the food budget, we can determine how many households have access to sufficient food. The way we assess food system performance explains why richer households in all countries are better protected from the economic consequences of disruptions or why poorer households are more likely to be affected by those disruptions (Devereux et al., 2020).

If it is estimated that eight percent of people do not have regular access to sufficient food, then the food system's performance level is 92 percent. Once the required inputs (e.g., total kWh per day) are determined, we can calculate the inputs' required budget. In the presence of a disruptive event, all required inputs may not be available and therefore only available inputs are taken into consideration. The food budget is then calculated using the required budget and the share of the food price inputs. For example, if energy accounts for nine percent of the food price and the adjusted energy budget is found to be US$92 million per day, then the food budget is $92 m/0.09 = $1,022 million per day. With the aid of average household disposable income and the budget share for total food, we can determine the food system's performance level. For example, if the average

Fig. 3 The process of measuring the resilience of a food system

food budget is \$1,050 per household, and if the budget share for total food is 10 percent of the household's disposable personal incomes, then households with disposable personal incomes less than \$1,050/0.1 = \$10,500 (Threshold income = \$10,500) cannot afford a healthy diet.

6 Labor intensity for food systems

The cost advantages that business establishments obtain due to their operation scale apply to food production, and economies of size (or scale) exist in agricultural production. In general, the average cost per unit of production decreases as the farm's size increases (Duffy, 2009). Increasing the production scale also reduces the amount of effort (or percentage of labor) used in the production process (labor intensity). Such improvements are possible because of the adoption of labor-saving and mechanical technologies that are economically justifiable for large scale production. As the size of farms (the number of hectares(ha)) increases, the amount of labor required per unit of production declines (Angeles-Martinez et al., 2017). Agricultural employment data separated by farm size is very lacking. A conservative approach would be to use a fixed amount of labor per ha (or per livestock inventory) and generalize such ratios to cases involving farms with different centralization levels.

The amount of labor needed in a food production and distribution process primarily depends on the quantity of food produced and the amount of human labor needed for transporting the produced food to consumers. The former is calculated based on the food demands (e.g., Table 1), while the latter is a function of the distance between the production unit and its consumers and the food quantity. The amount of labor needed to produce and distribute the food can be calculated as follows:

$$Labor = \sum_{i=1}^{NoC} C_i \times f_{labor}(C) + \sum_{i=1}^{NoC} (C_i \times D_i) \times f_{labor}(C, D) \tag{4}$$

where labor can be expressed as labor-hours or number of workers, NoC is the total number of consumers, C is the food demand per consumer, and D is the distance between the production unit and its consumers.

It is important to know how the food demand will determine the amount of labor, $f_{labor}(C)$, and quantify the labor needed to transport the produced food to consumers, $f_{labor}(C, D)$. This section provides details about the relationship between labor intensity and food production.

For vegetables, the vegetable food group's labor intensity can be specified using the U.S. principal vegetable in a fresh market for 27 vegetable types. The data is obtained from the annual vegetable statistics published by the National Agricultural Statistics Service (NASS) of USDA (NASS, 2020). With estimated employment of 230,700 people and an estimated

0.96 million ha used for fresh vegetable production, the ratio of 0.039 workers per hectare is used in the analysis. As shown in Fig. 4a, the $f_{labor}(C)$ for vegetable can be written as:

$$f_{labor}(C) = 21.4 \times (C^3) - 289.7 \times (C^2) + 14299.2 \times C$$

where C is the demand for vegetables in billion kg. For example, the labor needed to produce 15.19 billion kg of vegetables is estimated to be 225,586 people.

The labor intensity for the fruit food group can be specified using a comparison between U.S. fruit production and production per ha. The data for six fruit types, including cantaloupe, grapefruit, honeydew, lemon, orange, and watermelon, is obtained from USDA Fruit Yearbook Tables (USDA, 2020a, b) and aggregated to calculate the labor intensity for fruit production. With estimated employment of 356,770 people involved in fruit production and an estimated 1.04 million ha used for fruit production (USDA, 2019a, b), the ratio of 0.055 workers per ha is used in the analysis. As shown in Fig. 4b, the $f_{labor}(C)$ for fruit can be written as:

$$f_{labor}(C) = 2.8 \times (C^3) - 160.8 \times (C^2) + 13310 \times C$$

where C is the demand for fruit in a billion kg. For example, the labor needed to produce 25.4 billion kg of fruit is estimated to be 337,860 people.

The grain food group's labor intensity can be specified using a comparison between eleven selected crops (e.g., maize, wheat or rice) and production per ha. The main source of data is the Census of Agriculture that is a complete count of U.S. farms and ranches (USDA, 2017). With estimated employment of 498,220 people and an estimated 91.7 million ha used to produce the selected crops, the ratio of 0.0008 workers per ha is used in the analysis. As shown in Fig. 4c, the $f_{labor}(C)$ for vegetable can be written as:

$$f_{labor}(C) = 0.00001 \times (C^3) - 0.001 \times (C^2) + 528 \times C$$

where C is the demand for grain in a billion kg, for example, the labor needed to produce 8.1 billion kg of rice is estimated to be 4,320 people.

The labor intensity for the dairy food group can be specified using a comparison between U.S. milk production and production per cow. The dairy data is obtained from the reports produced by the USDA (USDA, 2020a, b). With estimated employment of 244,880 people in dairy farms and an estimated 9.336 million cows in the U.S., the ratio of 0.026 workers per cow is used in the analysis. As shown in Fig. 4d, the $f_{labor}(C)$ for dairy can be written as:

$$f_{labor}(C) = 1.006 \times (C^3) - 411.4 \times (C^2) + 44550 \times C$$

where C is the demand for dairy in billion kg. For example, the labor needed to produce 45.2 billion kg of dairy is estimated to be 251,460 people.

Fig. 4 The relationship between labor intensity and production of (**a**) vegetable, (**b**) fruit, (**c**) grain, (**d**) dairy, (**e**) protein, and (**f**) oil
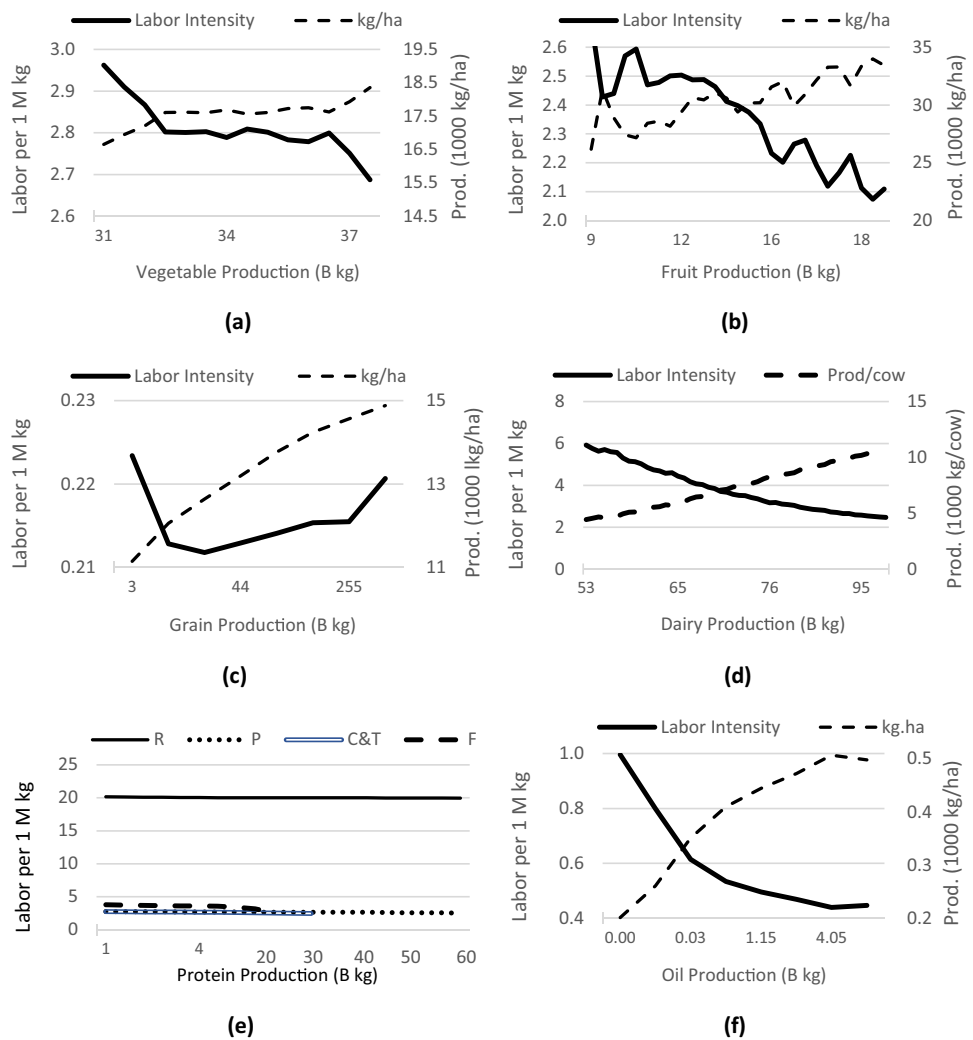
In the absence of protein food data separated by the production scale, the relationship between the labor intensity and protein food production may be achieved by recent survey studies. Strong evidence of size economies is up to a point in confined livestock operations like poultry, hogs, and dairy on the livestock sector (Rada & Fuglie, 2019). The information can be available implicitly in the food products such as maize that are exclusively used as feed for livestock (Sheng et al., 2019). A recent study by Xia et al. (2020) on the relationship between land size and productivity in the livestock sector in China and a recent analysis by Sheng and Chancellor (2019) on farm productivity according to farm size in Australia were used to find the amount of labor needed to produce protein foods based on the scale of production. Both studies found that the labor intensity is negatively correlated with the production scale. Figure 4e shows the relationship between the labor intensity and protein food production for four sub-categories including red meat excluding pork (labeled R), pork (labeled P),

chicken and turkey (labeled C&K), and last fish and seafood (labeled F). The $f_{labor}(C)$ for protein can be written as:

$$f_{labor}(C) = -132 \times (C^2) + a \times C$$

where C is the demand for protein in billion kg, a is a constant term and equals to 9956 for the red meat except pork, 3261.3 for pork, 4041 for chicken and turkey, and 3837 for fish and seafood.

The oil food group's labor intensity can be specified using a comparison between three oilseed crops including canola, safflower, sunflower, and production per ha. The main source of data is the Census of Agriculture (USDA, 2017). With estimated employment of 33,550 people and estimated 8,370 hectares used to produce the oils, the ratio of 0.25 workers per ha is used in the analysis. As shown in Fig. 4f, the $f_{labor}(C)$ for vegetable can be written as:

$$f_{labor}(C) = 46.2 \times (C^3) - 620.4 \times (C^2) + 6380 \times C$$

Fig. 5 A simulation application for a centralized food system in the state of Texas, USA
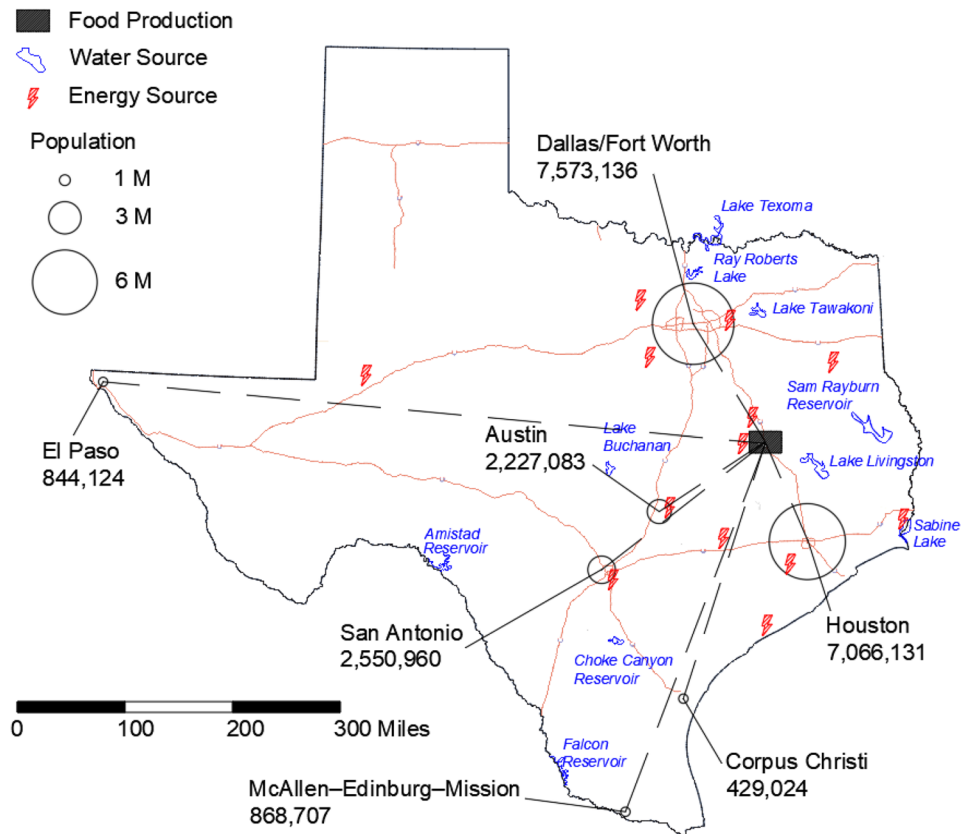
where C is the demand for oil consumption in billion kg, for example, the labor needed to produce 5.4 billion kg of oil is estimated to be 30,480 people.

The second part of Eq. 4 calculates the amount of human labor needed for transporting the produced food to consumers. In the United States, truckers are permitted to drive a maximum of 11 h per day. Therefore, we can assume that a trucker is expected to travel 1,593,251 km per year on average (based on the 252 working days per year). If we use the average of 21,772 kg payload for the trucks, then the second part of Eq. 4 can be written as:

$$f_{labor}(C, D) = 10.45 \times C \times D$$

where C is the demand for food in billion kg, and D is the distance between the production unit and its consumers in km. For example, the labor needed to transport 6.8 billion kg of food to 160.9 km is estimated to be 12,080 people.

7 Simulation analysis of the impact of disruptions on the food system

To demonstrate the use of the methodology proposed in this article, we performed a simulation using a hypothetical food system fed with demographic data and data on water and energy sources within the state of Texas in the USA

(see Fig. 5). The total number of consumers was limited to the top seven largest metropolitan areas in Texas (NoC = 7) that accounted for 84 percent of the state's total population (which was over 29 million at the time of the study). The top ten largest lakes and reservoirs were used as the input water sources, and the top thirteen petroleum refineries and power stations (based on production capacity) were used as the input energy sources. Proximity to the consumers and water and energy sources are three preferences for locating the production unit(s). Disruptions on the food system included labor shortage, and loss of water or energy supply.

Table 3 Total water and energy inputs to meet the food demand of the simulation model

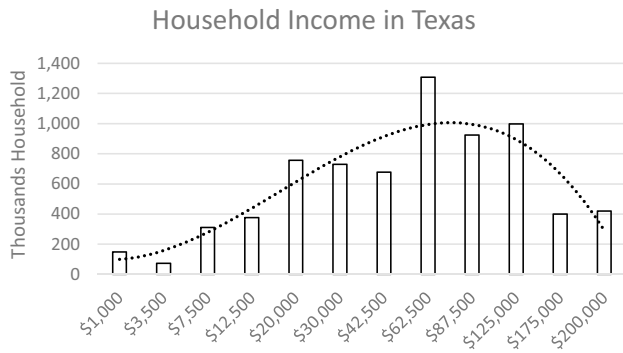| Category	Consumption (M kg per day)	Water requirement (M Liter per day)	Energy requirement (M Wh per day)
Vegetables	10	3241	6,651.8
Fruits	6.5	6316.7	9,315.6
Grains	3.9	6381	6,683.6
Dairy	13.3	13534.3	10,0064.4
Protein Foods	3.2	25,419	3,619.8
Oils	0.59	1360	659.5
Total	*35.6*	*56,253.4*	*36,994.9*

Fig. 6 Household income distribution used in the simulation for Texas, USA

The resilience was calculated for the food system with different degrees of centralization. The labor input to meet the food demand in the simulation was calculated based on the empirical data in Fig. 4. The data in Tables 1 and 2 were compiled to determine the water and energy inputs. The water and energy requirements to meet the food demands in Texas are listed in Table 3.

The fixed cost (FC) of water and energy was assumed to be US$1 per 1261.8 Liter of water and US$1 per 8.3 kWh of energy, and the variable cost (VC) assumed to be US$1 per 12,618 Liter per 161 km and US$1 per 50 kWh per 161 km. The equivalent energy needed to transport the produced food was assumed to be 2 KWh per km, and we used the average of 21,772 kg payload for the trucks. Figure 5 shows a scenario in which one production unit is located near the consumers. These cost values show that the water accounts for 0.7 percent, and energy accounts for 8 percent of the food price in the state of Texas, which are relevant to the costs of food production (FAO, 2016). The budget share for total food per household was assumed to be 10 percent of the annual household incomes. The degree of centralization (DoC), and water and energy costs for the food system shown in Fig. 5 are calculated as:

$$DoC = \frac{NoC}{NoP} \times \frac{\sum_{i=1}^{NoC}(C_i \times D_i)}{\sum_{i=1}^{NoC}C_i} = \frac{11}{1} \times \frac{5430 \times 10^6}{35.5 \times 10^6} = 1718\ km$$
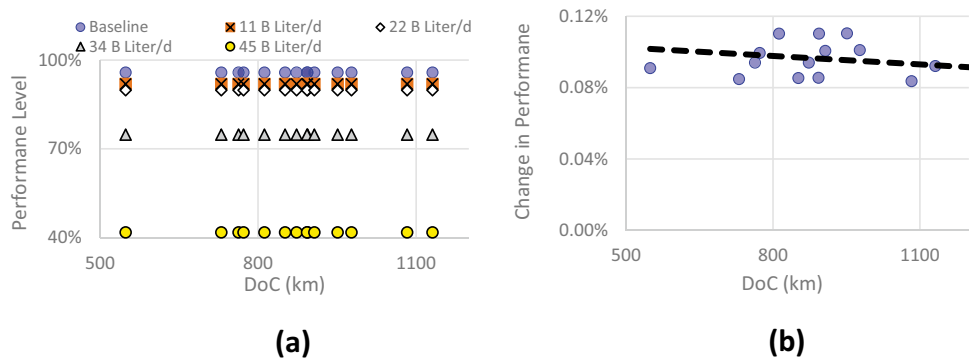
Water cost = Input x (FC + VC x D) = $14,860.6 \times 10^6$ x (3 + 0.3×0.36)/1000 = \$46.2 M.

Energy cost = Input x (FC + VC x D) + FC $\times 2 \times \sum_{i=1}^{i=7}$ $(Food\ Demand_i/48,000 \times D_i) = 36,994.9 \times 10^3$ x ($12 + 2 \times 0.022$) + $12 \times 2 \times 542,318 = \$452.1$ M.

In the case of water disruption, the water input dominates the food price. Therefore:

Food price per household = \$46.2 M/0.1%/7.4 M = \$892

As an example in this simulation, if a Texan household spends an average of 10 percent of their annual incomes on food, households with an annual income of less than \$8,920 cannot afford a healthy diet. Figure 6 shows the household income distribution used in the simulation. According to this income distribution, 318,806 out of 7.4 million households or 4.3% of the population cannot afford a healthy diet. The recommended amounts of each food group listed in Table 1 are the basis for a healthy diet. Thus, the performance level is set to be 95.7%.

The performance level is calculated for the food production units with different DoCs and based on five disruptive scenarios related to water. These scenarios included a baseline and water supply interruptions for 11.3 billion Liter per day (B Liter/day), 22.7 B Liter/day, 34 B Liter/day, and 45.4 B Liter/day. Figure 7a shows the performance levels for these scenarios. The strength and direction of the relationship between DoCs and resilience of the food system experiencing a disruptive water event is shown in Fig. 7b. This relationship is analyzed statistically using Pearson's correlation coefficient. As shown in Fig. 7b and Table 4, the Pearson correlation between the resilience and DoC was weak (correlation coefficient = -0.277) and not statistically significant at the 95% confidence level.

In the case of energy disruption, the energy input dominates the food price. Therefore:

Food price per household = \$452.1 M/8%/7.4 M = \$764

In this calculation, households with an annual income of less than \$7,640 cannot afford a healthy diet. This is consistent

Fig. 7 Impact of water disruptions on the food system (**a**) simulation results for five scenarios, (**b**) correlation analysis between degree of centralization and resilience

(a)

(b)

Table 4 The Pearson Correlation Coefficient between degree of centralization and resilience of the food systems

Disruption on Input	Pearson Correlation	Sig. (2-tailed)
Water	-0.277	0.237
Energy	-0.803	0.000
Labor	0.961	0.000

with the poverty line of $27,750 for a household of four and 10 percent food budget share (as used in the calculation) per the US Department of Health and Human Services (HSS) 2022 Poverty Guidelines (HSS, 2022).

in Texas According to the income distribution, 286,136 out of 7.4 million households or 3.9% of the Texan population, cannot afford a healthy diet. Thus, the performance level is set to be 96.1%. The performance level is calculated for the food production units with different DoCs and based on five disruptive scenarios related to energy. These scenarios include a baseline and energy supply interruptions for 5 GWH/day, 10 GWH/day, 15 GWH/day, and 20 GWH/day. Figure 8a shows the performance levels for these scenarios. The strength and direction of the relationship between DoCs and the food system's resilience experiencing an energy disruptive event are shown in Fig. 8b. This relationship is analyzed statistically using Pearson's correlation coefficient. As shown in Fig. 8b and Table 4, the Pearson correlation between the resilience and DoC is strong (correlation coefficient = -0.803) and statistically significant at the 95% confidence level.

In the case of a labor disruption, the labor input dominates the food price. The number of people needed to meet each food system's food demand is calculated based on Eq. 4. The number of people for the centralized food system shown in Fig. 5 as 307,838, and as the DoC decreases, the number of people needed increases. We used the data provided by the Economic Research Service of the USDA to calculate the food budget based on the labor cost. For every one person employed directly on farm, 4.2 people are working in the overall agricultural and food sectors. Labor accounts for 12 percent of production expenses for all farms (e.g., protein foods, grain, oil, and dairy food groups), 43

percent for greenhouse and nursery operations (vegetable food group), and 39 percent for fruit and tree nut operations (fruit food group) (USDA, 2018). The median income of US$59,570 per year was used per worker. The performance level was calculated for the food production units with different DoCs and based on five disruptive scenarios related to labor shortage. These scenarios included a baseline, and labor shortage of 50, 100, 150, and 200 thousand people. Figure 9a shows the performance levels for these scenarios. The strength and direction of the relationship between DoCs and resilience of the food system experiencing a labor shortage are shown in Fig. 9b. This relationship is analyzed statistically using Pearson's correlation coefficient. As shown in Fig. 9b and Table 4, the Pearson correlation between the resilience of the food system in the event of labor shortage and DoC is very strong (correlation coefficient = 0.961) and statistically significant at the 95% confidence level.

8 Limitations of the study

As for all simulations, our study has limitations rooted in its scope and assumptions. First, the models and simulations were concentrated on the supply side of food systems. To develop and optimize food resilience strategies, both supply and demand sides must be considered. The food demand inputs in the study are deterministic; the food consumptions are known and remain unchanged during and after the disruptive events. Even if we use the eating patterns and dietary limits recommended by food agencies to determine the food demand, in practice, food consumption patterns change over time and adapt to new circumstances. The changes in eating habits during COVID-19 is a good example. At-home consumption increased, but out-of-home consumption came to nearly a standstill and major changes in customer behavior and demand have been observed. Consumer behavior changes differently in emergencies (Wang et al., 2020). A recent study investigated the immediate impact of the COVID-19 pandemic on eating habits and lifestyle changes among the Italian population aged over 12 years through a structured questionnaire and showed obvious changes in eating habits and adherence to the Mediterranean Diet pattern

Fig. 8 Impact of energy disruptions on the food system (**a**) simulation results for five scenarios, (**b**) correlation analysis between DoC and resilience
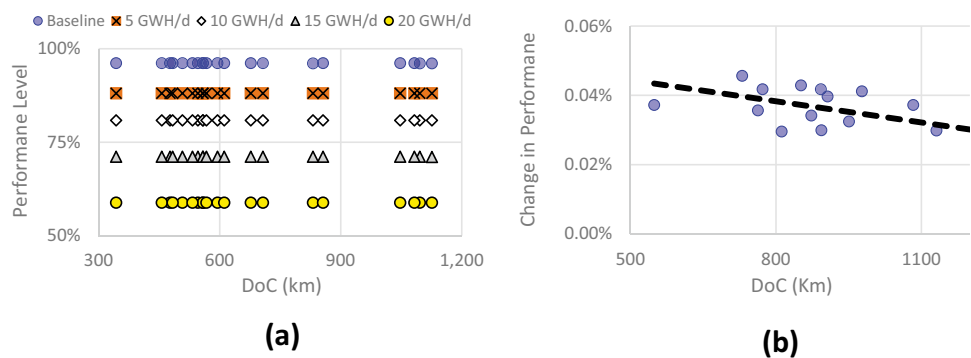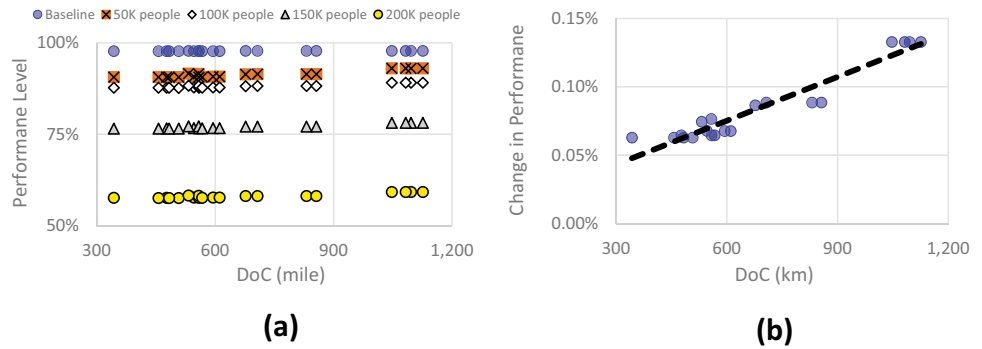
Fig. 9 Impact of labor shortage on the food system (**a**) simulation results for five scenarios, (**b**) correlation analysis between DoC and resilience

(a) (b)

(Di Renzo et al., 2020). Modeling the impact of water, energy, or labor shortage interruptions on food production is only the first step to creating resilient food systems. Therefore, future studies should also examine the demand side changes when the food supply is disrupted.

Second, we only studied the impact of three inputs/resources (i.e., energy, water, and labor) on the performance of the food system. In contrast, capital resources heavily influence the use of other inputs/resources. Most of this influence undoubtedly corresponds to the degree of centralization (included in this study). Increasing the scale of production makes the adoption of labor-saving and mechanical technologies justifiable. However, investment in capital resources is not always positively correlated with the scale of production. For example, controlled-environment agriculture (CEA) optimizes the use of resources such as water, energy, and labor. Production in a CEA usually takes place within a distributed food system (e.g., greenhouse) to maintain optimal growing conditions throughout crop development. The impact of capital resources on food system inputs makes it difficult to generalize the food group's food productivity rates. Hence, efforts should be made on links between specific capital resources and inputs (e.g., robotic milking machines and labor).

Third, we assumed that the land required to produce the food is available. Land is a finite resource, already under heavy stress, but its location determines the air temperature and sunshine duration for agricultural fields. To deal with this limitation, the simulation model processed the resilience of the food systems within the state of Texas, where they share the same type of climate zone. It is necessary to expand the model inputs to include other natural resources to ensure the proposed method's applicability to different climate zones.

Fourth, resilience is measured in this study based on the absorptive system capacity. A more comprehensive approach is to use a resilience metric that incorporates all three resilience capabilities (absorptive, adaptive, and restorative). The performance level in this study is measured post-disruption immediately and before any recovery efforts. In practice, we make some adjustments to maintain continuity of operations of essential services. Ultimately, the food system would achieve

a new stable level after recovery efforts have been exhausted. The time and cost to complete initial adjustments and to final recovery are additional dimensions to be taken into consideration in measuring the resilience of the food system.

Fifth, the lack of employment data to directly link the labor intensity to the degree of centralization made us use the production scale as an intermediary variable. Having employment data of food systems producing similar amounts of food at different degrees of centralization, we are able to statistically measure and assess how decentralization of food systems impact their resilience in the event of the labor shortage.

Last, cascading failures were not considered in this study to analyze the impact of water, energy, or labor shortages on the system's productivity. The food, energy, and water systems are interdependent, and a disruptive event in one system can trigger the failure of other systems, and so on. For instance, interruptions in the water system will be followed by a cascading failure of interconnected energy systems if no actions are taken to maintain its essential functions. Apparently, modeling cascading effects is not necessary to draw conclusions on such impacts on the system productivity in terms of the degree of centralization but could expand research paths.

9 Conclusions and discussion of results

This study investigated the relationship between the degree of centralization (DoC) of food systems and their resilience to disruptions in the supply of energy, water, or labor using a quantitative method. It used an example analysis of the situation in the state of Texas, USA. The DoC is developed to quantify how a food system is structured; more centralized, or more distributed. The results contribute to understanding ways to build more resilient food systems capable of adapting to labor, energy, or water disruptions. We showed that money can be used as a common basis to draw an analogy between different areas of resilience, such as the labor intensity, energy and water requirements, and last performance of food systems. A food system's resilience to a specific disruptive event can be determined by total recovery effort, which is a function of recovery costs. A more resilient system can

recover from a disruptive event and return to normal or improved operations at a lower cost. This common basis also enables us to include household income (as a socio-economic factor) in the analysis.

To measure the resilience of a system in responding to disruptions in the input resources (e.g., supply of labor, water, or energy), we should first figure out how dependent the system is on those resources. Again, the use of money as a common basis enabled us to compare these three essential resources' impact. The cost of labor required to produce a production unit is significantly higher than the cost of energy or water. The labor accounts for 12–43 percent of production expenses for food productions, while the water accounts approximately for less than 1 percent, and the energy accounts for approximately 8 percent of the food price. Therefore, the food systems are more susceptible to shocks in the labor supply than energy or water (which is consistent with our simulation results). Specifically, the protein food group is much more labor- and water-intensive than other groups. Considering the recommended intake amounts, the grains food group is relatively more energy-intensive than other groups, although it is the least labor-intensive one.

The data collected regarding the water and energy requirements of producing and supplying food showed that the dairy farming and milk production is more vulnerable to energy shocks, while protein foods are more vulnerable to water shocks than others. Animal-based protein foods are generally more resource-intensive to produce than plant-based foods. Although cultivated meat and fermentation are still energy-intensive, an accelerated growth is anticipated as technical advances can mitigate the environmental impact of our food system and ultimately supply sufficient protein with fewer energy and water resources. Economies of scale occurs when more units of a good or service can be produced on a larger scale with (on average) fewer input costs. The measurement of economies of scale in the US food system has utilized in our methodology for the resilience assessment of centralized and distributed food systems. A food system with large volumes of production can significantly reduce the cost of production because their expenses are distributed over a more considerable number of food products. The analysis of the relationship between labor intensity and production of six major food groups including vegetables, fruits, grains, dairy, protein foods, and oils showed that they all benefit from economies of scale as such centralized food systems have allowed fewer farmers to produce more food. The economies of scale and effective use of limited resources have pushed the US food system towards a more centralized system in the past thirty years.

The potential cost savings resulted from centralized systems do not necessarily improve food system resilience. A simulation using a hypothetical food system fed with demographic data and actual information regarding the water

and energy sources within the state of Texas in the USA was performed. The DoC is calculated for different food systems, and the performance of the systems is measured for different disruption scenarios. The results of the simulation showed that centralized food systems can sustain their resilience (maintain their overall performance) to shocks when the water and energy disruptions are limited to 39% and 13%, respectively. Once the water supply interruptions are higher than 39% or the energy supply interruptions are higher than 13%, distributed food systems outperform the centralized systems. We can conclude that the decentralization of food systems can in fact, improve their resilience in responding to disruptions in the energy and water inputs. A negative correlation is found between the resilience and DoC for energy disruption scenarios. In contrast, achieving a more resilient food system in responding to labor shortage supports a push towards a more centralized system. A strong positive correlation is found between the resilience and DoC for labor shortage scenarios, and when the DoC goes up, the resilience of the food system goes up. This can be explained in part by the economies of scale because the adoption of labor-saving and mechanical technologies is economically justifiable for large scale productions (higher DoCs). Both centralized and distributed systems are more vulnerable to shocks in the labor than those in water and energy supplies. For example, if half of the water supply is disrupted for a food system, it is expected to lose only around 30% of the food production. In contrast, a food system can maintain only 56% of its performance when half of the required labor is not available. The lack of segregated data is more evident when we plan to understand how dependent the food system is on energy, water, and labor resources. Supporting the collection of datasets that can be used for the food system assessments should be given priority.

Declarations

Conflict of interest statement The authors declared that they have no conflict of interest.

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