Mapping Barriers to Food, Energy, and Water Systems Equity in the United States

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Abstract

Barriers to affordable, accessible, high-quality food, energy, and water systems (FEWS) harm social equity. Connections within and across FEWS suggest that co-occurring barriers to equity can compound vulnerability. We hypothesized that barriers to FEW resources are strongly associated with geographic location, both within and across FEWS, as they rely heavily on localized sociopolitical and natural environments. This study explored the geographic relationships between FEWS barriers and social equity through a spatial analysis of census tracts within the United States. Cluster analyses showed that all FEWS barriers had a positive spatial autocorrelation (Moran's I = 0.12 - 0.94), with energy barriers being the most spatially clustered and affordability barriers being the least spatially clustered. In 54% of census tracts, we observed the co-occurrence of low barriers to water quality and access. Barriers to FEWS affordability almost always co-occurred in parallel (e.g., high barriers to affordability in one system co-occurred with high barriers to affordability in another system). Finally, we developed a spatial index of the barriers to FEWS equity to determine vulnerability at the census tract scale, which had a positive spatial autocorrelation (Moran's I = 0.41). Clusters and intersections of FEWS equity barriers suggest that resources are interconnected, resulting in additional challenges for people living in these areas. The maps of barriers to equity in FEWS are useful tools that could help stakeholders (e.g., federal agencies, city planners, utilities) distribute FEWS resources fairly and begin engagement with communities about FEWS barriers in their local context.

Highlights:

- Barriers to food, energy, water system (FEWS) resources impede equity
- Barriers to FEWS resources were evaluated at the US census tract scale
- All barriers to equitable FEWS resources were spatially clustered
- Barriers to FEWS affordability often co-occurred, enhancing vulnerabilities
- A US FEWS Equity Barrier Index was developed to support effective decision-making

Keywords: Social equity, Socio-environmental Index, Resource Affordability, Resource Access, Resource Quality, Environmental Justice

1 Introduction

Food, energy, and water systems (FEWS) constitute an interconnected biophysical nexus that influences and relies upon sociopolitical and natural environments (Kaddoura and El Khatib, 2017; Helmstedt et al., 2018; Vörösmarty et al., 2023a). Nexus research is a growing field primarily focused on increasing resilience and reducing environmental damage (White et al., 2017). FEWS are constantly in flux, facing increasing pressure from climate change and population growth that heighten demands on the systems (Endo et al., 2017; Hinrichs, 2014; James and Friel, 2015), as well as more urgent social demands to improve capacity to adapt to FEWS disruptions (Bergendahl et al., 2018; Biggs et al., 2015; Food and Agriculture Organization, 2014). Furthermore, increased stress on FEWS caused by climate change is likely to cause greater harm to populations who are already economically and socially vulnerable (US Environmental Protection Agency, 2021; Younger et al., 2008). These stressors motivate research focused on identifying tradeoffs for the sustainable intensification of FEWS (Kaddoura and El Khatib, 2017; Sodiq et al., 2019; White et al., 2017), such as increasing agricultural production while protecting valuable water resources. Although the nexus approach has been applied in a variety of contexts, we define the FEWS nexus as a framework for studying and managing F, E, W systems that recognizes their interconnectedness and aims to balance human demands with sustainable development (Estoque, 2023). In this context, advocates call for equitable resource allocation, which can be supported by integrating social equity into the FEWS nexus approach (Stone et al., 2023).

FEWS resources are critical to human well-being, and barriers to equitable production and distribution can damage communities (Younger et al., 2008). Economically and socially vulnerable populations are more likely to be hurt by environmentally damaging FEWS infrastructure such as food processing facilities, energy conversion plants, and wastewater discharges (Bullard, 1994; US Environmental Protection Agency, 2021; Younger et al., 2008; Zimmerman, 1993). FEWS infrastructure, along with social, economic, and environmental conditions, can create barriers to FEWS that hurt social equity. Stone et al. (2023) found that equitable provisioning of FEWS resources involves three primary factors: affordability, access, and quality. Gaining a greater understanding of barriers to affordable, accessible, and good-quality FEWS resources can help alleviate existing and future inequities that are likely to be exacerbated by climate change.

Identifying useful measures of barriers to FEWS is important to understand the biophysical and social characteristics that influence equitable and sustainable resource provisioning. Yet, it is often difficult to create adequate metrics because they are complex and relational. For example, a metric measuring “affordability” requires a nuanced approach. Cost data for individual items or resources are insufficient, as many other factors determine if something is "affordable" (Teodoro, 2019), including the dynamic prices and fungibility of other essential household expenses, including FEWS resources (e.g., electricity and food (Doremus et al., 2022) as well as non-FEWS essentials (e.g., housing costs, childcare). Likewise, “access” is complex because it can involve both spatial proximity and the presence of infrastructure necessary to obtain FEWS resources. Quality is similarly nuanced, particularly in the case of FEWS resources where it can be difficult to measure on a household scale (Stone et al., 2023).

FEWS are heavily influenced by factors, such as geology, climate, and biome, leading to localized or regional system characteristics (Albatayneh, 2023; Huntington et al., 2021; Vörösmarty et al., 2023a). For example, water systems can be highly localized depending on watershed or aquifer characteristics; furthermore, most water treatment and distribution is conducted at the municipal scale. Additionally, FEWS are closely interconnected, meaning changes to one system can significantly affect the other two systems in the same area (Newell et al., 2019; Vörösmarty et al., 2023a). Illustrating this point, local and regional characteristics influence whether agricultural production necessitates irrigation or artificial drainage, which in turn affects water quality. Because of the local and regional nature of biophysical FEWS, spatial trends and intersections of the systems could also be present in barriers to affordability, accessibility, and quality that impede equity. Co-occurrence, or spatial intersections of multiple barriers, could create a compounding effect and bring additional challenges for people living in these census tracts.

Spatial analysis is a useful way to visualize trends at a variety of geographic and governance scales (e.g., Albert et al., 2017; Pappalardo and Debizet, 2020). Clustering or hotspot analysis can identify large groups of similar values, suggesting that the system has a widespread effect on the resource barriers or that the data are more affected by local sociopolitical influences or the natural environment (e.g., Wang and Varady, 2005). By mapping multiple datasets at the same scale (e.g., census tract), we can identify where trends overlap or co-occur, which can provide information about the degree to which populations in these census tracts might be disadvantaged (e.g., The Biden Administration, 2023). Indices that combine metrics spatially can aid in understanding complex physical, social, and cultural interactions and their spatial distributions (e.g., Albrecht & Ramasubramanian, 2004; Nar & Nar, 2019; Shu et al., 2021; Zhu et al., 2019).

Identifying FEWS barriers and their spatial distribution can help to understand the biophysical and sociopolitical factors that impede FEWS equity. Spatial analysis and visualization of FEWS barriers can help engage stakeholders and disadvantaged communities to prevent further harm that often occurs when decision-makers are unaware of preexisting inequities in accessing the biophysical systems they administer (Hoolohan et al., 2018; Liang et al., 2020). Historically, decisions about FEWS and the environment are largely the result of sociopolitical factors that influence policy (i.e., determined by economics, culture, power, and politics), as opposed to scientific findings (Desikan et al., 2023). Consequently, policy often neglects underrepresented and vulnerable communities that have limited access to the policy process or are underrepresented in governing bodies (Desikan et al., 2023). In the United States (US), recent federal programs, such as Justice40, have highlighted the need for identifying disadvantaged populations as they relate to climate change and involving them in the process to build resilience capacity (The Biden Administration, 2023; Watson, 2023). Similarly, there is a need to identify and engage populations experiencing barriers to affordable, accessible, and good-quality FEWS resources to build more sustainable and just systems.

In this study, we identified affordability, access, and quality barriers to FEWS resources. Our objectives were to i) spatially examine potential clusters or hotspots of barriers to each FEWS resource, ii) evaluate whether barriers co-occur spatially, and iii) create an index of barriers to FEWS equity. We hypothesized that we would find clusters of barriers, because we expect that barriers to FEWS resources, like FEWS, also rely on local biophysical systems and sociopolitical factors such as economics, policies, and culture. The FEWS Equity Barriers Index we developed identifies trends and disadvantaged populations at the census tract scale that can inform FEWS governance and future research.

2 Materials and Methods

Building on the FEWS equity themes from the Stone et al. (2023) systematic literature review, which synthesized how social equity was incorporated in FEWS literature, we identified one measure each of affordability, access, and quality representing each Food-Energy-Water system to assess trends in barriers to resources and create a United States (US) FEWS Equity Barriers Index. We identified available nationwide data, prioritizing data collected at the census tract level from reputable and publicly available sources. The ten indicators used to analyze and build a FEWS Equity Barriers Index were based on the fit for each equity theme, data availability, and national coverage (Table 1, Figures S1-S10).

Indicators were selected to represent, as closely as possible, the FEWS barriers or burdens experienced by each US census tract. Affordability data for food, energy, and water systems were calculated as the "burden" of each system, or the annual cost divided by the median family income for each census tract (Teodoro, 2019). We define access as the ability to obtain FEWS resources, where barriers to access are indicated by the prevalence of food deserts, frequent power outages, and households lacking complete plumbing. Food deserts were selected as the food access indicator due to their emphasis on spatial access which has more limited overlap with food affordability than other indicators considered (e.g., U.S. Supplementary Nutritional Assistance Program enrollment).

For energy access, some areas of the country are more likely to experience inclement weather patterns that can disrupt electricity access; therefore, we selected the Customer Average Interruption Duration Index (CAIDI) measure that includes Major Event Days (i.e., electricity outage caused by a major event; Committee of the IEEE Power and Society, 2012) averaged over a five-year period (2017-2021). Our energy access barrier measure may introduce some confounding variables between climate impacts and energy system performance. While this approach limits our ability to isolate purely operational issues, we believe it provides a more comprehensive assessment of overall barriers to energy access. This method allows us to capture the complex interactions between climate events, energy system infrastructure, and FEWS equity, highlighting areas where infrastructure improvements could enhance system resilience and ensure more equitable access in the face of increasing climate uncertainties. We also explored barriers to resource quality; food quality is gauged by the ratio of unhealthy to total food retailers, water quality by regulatory violations in community water systems, and energy quality through household Energy Consumption Intensity (ECI). The latter reflects a type of energy burden that is particularly relevant for low-income and marginalized households unable to afford energy-efficient housing, underscoring social equity concerns (Buylova, 2020; Reames, 2016; Tong et al., 2021).

Addressing FEWS issues, both now and in the future, requires accounting for increasing uncertainties due to climate change, particularly those caused by weather-induced hazards (Alhanaee et al., 2017; Bärring and Persson, 2006; Memarzadeh et al., 2019). Climate change impacts are important at the community scale and are deeply intertwined with FEWS, potentially increasing the risk of widespread energy outages, reduced agricultural productivity, and decreased water potability (Vörösmarty et al., 2023b). To capture these complex interactions, we incorporated a Community Resilience metric from the US Federal Risk Management Agency's National Risk Index in our FEWS Equity Barriers Index. This metric assesses a community's ability to recover from climate-related disasters such as extreme weather, droughts, and wildfires (Zuzak et al., 2022). By including this indicator, our analysis considers a community's ability to bounce back from climate shocks and recognizes that those with limited recovery capacity face greater barriers to climate resiliency. This approach allows us to identify at-risk areas across the US where the complex relationship between climate risks and FEWS vulnerabilities may be most pronounced at the community level.

Table 1: Indicators of barriers to FEWS equity available in the US. The percentage of missing values was calculated after data cleaning (described in section 2.2), leaving 82,907 census tracts.

FEWS System	Equity Theme	Barrier Measurement	Data Source	Units	Data Range	Percentage of Missing Values
Food	Affordability	Food Burden: annual spending/household income	US Consumer Spending (Esri, 2022) US Bureau of Labor Statistics Consumer Expenditure Surveys (US Bureau of Labor Statistics, 2022) 2020 US Census (Walker and Herman, 2023)	cost:income ratio	0-5.9	<1
	Access	Percentage of population further than 0.5 miles (urban areas) or 10 miles (rural areas) from a supermarket	Food Access Research Survey (USDA Economic Research Service, 2022)	%	0-100	25
	Quality	Percentage of healthy food retailers out of total food retailers	Modified Retail Food Environment Index (Center for Disease Control and Prevention - Division of Nutrition, 2012)	%	0-100	36
Energy	Affordability	Energy Burden: annual spending/household income	See *Food Affordability* data sources	cost:income ratio	0-1.2	<1
	Access	2017 – 2021 Customer Average Interruption Duration Index (CAIDI)	Annual Electric Power Industry Report (US Energy Information Administration, 2021)	minutes	9.5-2146.6	0
	Quality	Average Household Energy Consumption Intensity (energy used for temperature regulation divided by the square footage of livable space)[1]	Modeled. ResStock Residential End Use Load Profiles (National Renewable Energy Laboratory, 2021) 2020 American Community Survey (US Census Bureau, 2020)	kWh/sqft	3.1-32.6	0
Water	Affordability	Water Burden: annual spending/household income	See *Food Affordability* data sources	cost:income ratio	0-0.4	<1
	Access	Percentage of households with incomplete plumbing	2020 American Community Survey (US Census Bureau, 2020)	%	0-83.3	0
	Quality	Maximum Number of Violations	Enforcement and Compliance History Online (US Environmental Protection Agency, 2022) (Internet of Water Initiative et al., 2022; SimpleLab and EPIC, 2022)	violation points	0-763	7
Climate	Resilience	FEMA National Risk Index – Community Resilience[2]	US Federal Emergency Management Agency (Zuzak et al., 2022)	index (0-100)	41.2-64.7	<1

[1] Relevant attributes between the ResStock load profiles and the 2020 census survey were identified (i.e., household size, income, state, urban/rural status, type of home, own or rent, fuel type used, and age of home) to model the energy consumption intensity for each census tract. A similar methodology was employed by Bednar et al. (2017).

[2] Obtained by subtracting the FEMA National Risk Index Community Resilience value from 100.

2.1 Spatial Analysis

Spatial autocorrelation tests Tobler's first law of geography: "Near things are more related than distant things" (Tobler, 1970). Variables with high spatial autocorrelation indicate patterns in the data, such as hotspots or clustering, that require further analysis. Clustering of high barriers indicates systemic issues influenced by the natural environment or regional sociopolitical factors (e.g., city, county, or state governance). Each indicator variable was tested for spatial autocorrelation using Global Moran's I calculated with the spdep package in R and queen criterion neighbors (Bivand, 2022; Bivand & Wong, 2018). Values of Moran's I range from -1 to 1, with negative numbers indicating spatial dispersion and positive numbers indicating spatial clustering (Moran, 1950). We then calculated the Local Moran's I values using a Local Indicators of Spatial Autocorrelation (LISA; Anselin, 1995) test, which identified clusters and outliers when compared to neighboring census tracts for each indicator variable. A threshold p-value of 0.05 was used for all statistical tests. Data analysis was performed in R version 4.1.2 (R Core Team, 2022). Maps and figures were created using the ggplot2 package in R (Wickham, 2016).

2.2 Data Cleaning and Normalization

As of 2023, there are 84,214 census tracts in the US. We removed census tracts that were missing median household income data (n=1,254) or had a population count of 0 (n=563) in the 2020 American Community Survey. Before locating co-occurrences and calculating the index, census tracts missing more than one indicator in each food, energy, or water system were removed from the analysis (n=9,681).

The indicator values for food affordability, energy affordability, energy access, energy quality, water affordability, and water quality had extreme outliers. For these indicators, we considered anything beyond the bottom 2.5^{th} percentile and above the 97.5^{th} percentile to represent the best and worst values. Thus, we capped values outside of below and above this range to be equal to the 2.5^{th} and 97.5^{th} percentiles, respectively. All indicators were normalized to a 0-100 scale,

$$x' = 100\ \frac{x - \min(x)}{\max(x) - \min(x)}$$

where the maximum and minimum are of each individual indicator *x*. For food quality and climate resilience, the normalized data were subtracted from 100 to obtain their complements. This step ensured all variables followed the same trend of lower values indicating more barriers to FEWS resources. This normalization results in values closer to 0 indicating low barriers, while values closer to 100 indicate high barriers to FEWS resources.

2.3 Identification of Co-Occurrences

After normalizing the data for each indicator, we identified co-occurrences of barriers both within and across the FEW systems. For each system, we identified values in the top and bottom quintiles (80th and 20th percentiles; Tong et al. 2021) for each barrier (affordability, access, and quality). We then identified census tracts where all three barriers had significant high or low values and identified the relationship as an intersection of high values (top quintile or more barriers), low values (bottom quintile or fewer barriers), or a mixed intersection (at least one high and one low quintile value; conflicting barriers).

2.4 Index Calculation

The FEWS Equity Barriers Index was computed with:

FEWS Equity Barriers Index = (0.3 * Averaged food barriers) + (0.3 * Averaged energy barriers) + (0.3 * Averaged water barriers) + (0.1 * Community Resilience)

Index values were calculated by taking the average of the three indicators (i.e., affordability, access, and quality) in each FEWS to get a separate value for each system. This step allowed us to still obtain a value for each system, even if there was a missing barrier value (Table 1). The weights used (0.3 and 0.1) ensured the climate indicator (community resilience) was not given more weight than any FEWS indicator. The final index values were then normalized to obtain a 0-100 scale.

3 Results

3.1 Variation of FEWS Equity Barriers by State

Mapping barriers to FEWS affordability, access, and quality shows regional and statewide trends (Figure 1). Barriers to FEWS affordability remain consistently high through Alabama, West Virginia, Mississippi, South Carolina, and Louisiana. Delaware and Connecticut had the highest population-weighted food access barriers due to the percentage of the population living far from a grocery store. Energy and water access barriers were highest in Louisiana and Alaska, respectively. Food quality barriers, or the proportion of unhealthy food to healthy food retailers in an area, were higher in the Southern US, Northeastern US, and Alaska. Energy quality barriers have the clearest regional trend of any FEWS barrier, with Northern states having higher barriers on average (Figure 1). Water quality barriers were considerably higher in West Virginia than any other state. Mapping average climate resilience by state shows that Western and Southern states and Alaska tend to be more vulnerable to climate change impacts than states on the East Coast or in the Midwest.

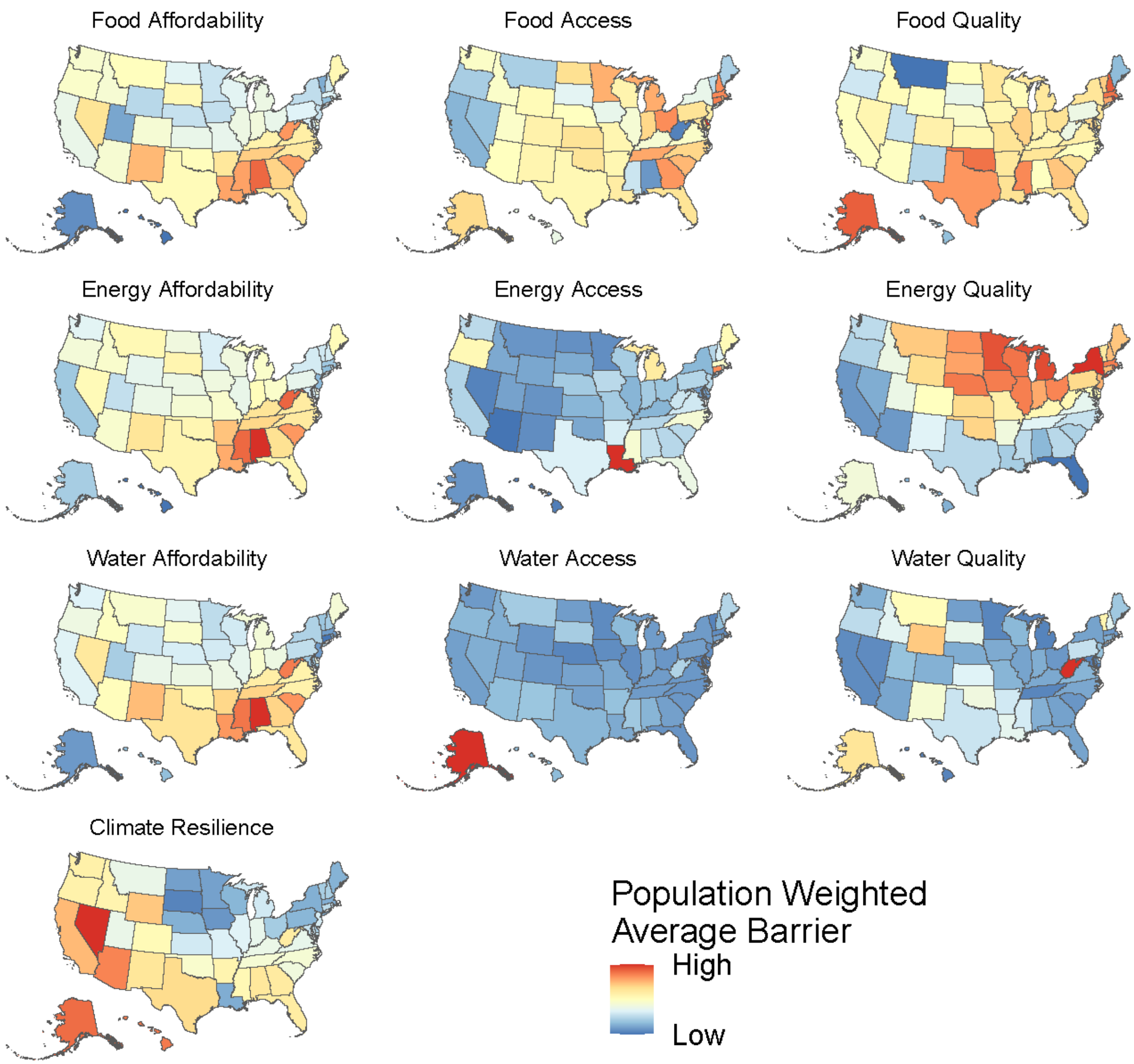

Figure 1. FEWS barriers mapped by US state. Higher values correspond to higher population-weighted barriers to FEWS equity.

3.2 Spatial Analysis

Each of the nine indicators contained a positive spatial autocorrelation based on Moran's I, ranging from 0.12 (low spatial autocorrelation) to 0.94 (high spatial autocorrelation; $p < 0.05$, Figure 2). High spatial autocorrelation of FEWS barriers suggests that the ability to obtain resources may be locally influenced by the natural environment or sociopolitical factors such as economics (e.g., cost of living, household income) and policies (e.g., assistance programs, FEWS regulations). While all barriers had a positive spatial autocorrelation and showed spatial clustering, some were not as clustered as others. For example, affordability barriers to FEWS were the least spatially clustered, with food affordability having the lowest Moran’s I value. Barriers to energy were among the most spatially correlated, likely due to the regional distribution of US energy infrastructure (Figures 1 and 2).

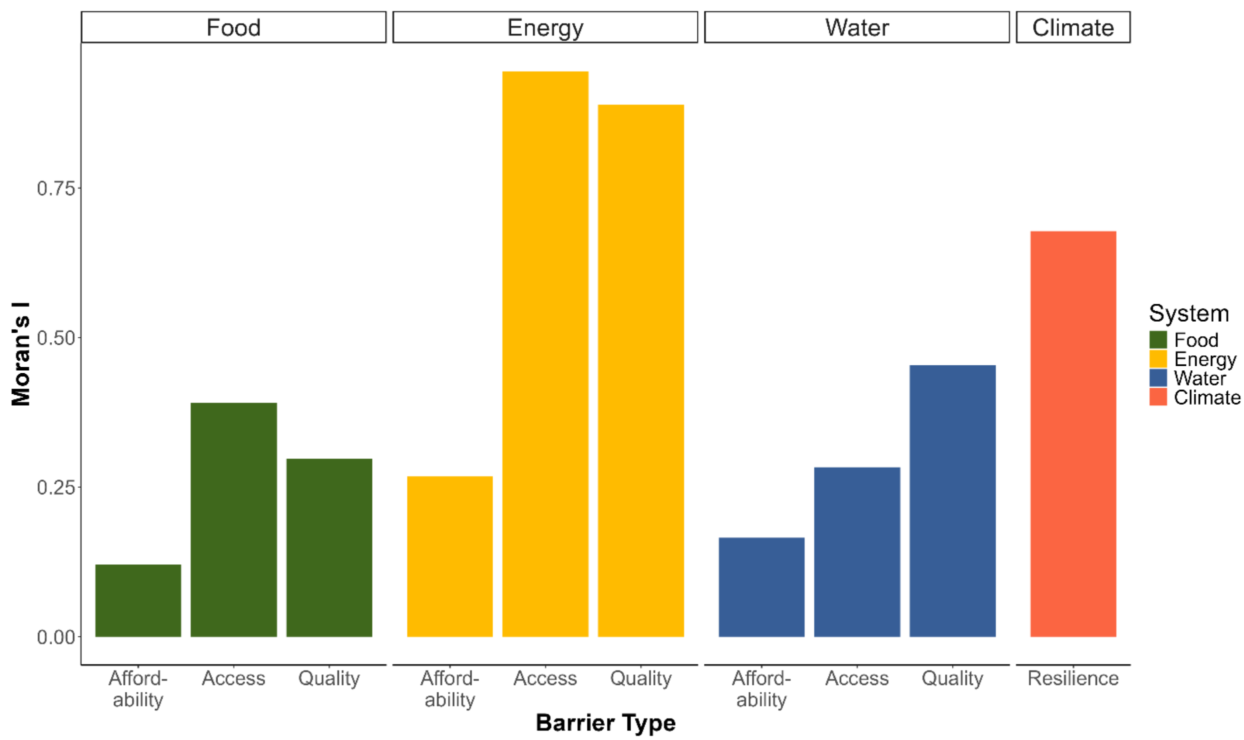

Figure 2: Degree of spatial autocorrelation of FEWS equity indicators across the US.

After energy barriers, the next most spatially correlated metric was the community resilience (Climate) value, followed by water systems. The large percentage of missing food access (25%) and food quality (36%) data (Table 1) influences Moran's I values because tracts with missing values are omitted in the calculation. Water systems are regionally connected (i.e., watersheds or aquifers); thus, we expected to observe more spatial trends in the water barriers, particularly for water quality (number of violation points at the Community Water System). However, compared to the other systems, water access and quality barriers were only moderately spatially autocorrelated (Moran's I of 0.28 and 0.45, respectively), showing less spatial trends than expected.

3.3 Co-Occurrences of Barriers

In both food and energy systems, co-occurrences were infrequent, occurring in less than 10% of census tracts (Figure 3-a). Barriers to equitable water systems co-occurred most often. In 17% of census tracts, there were co-occurring low barriers to water affordability, access, and quality. Low barriers to water access (houses with incomplete plumbing) and quality (community water violations) co-occurred in 54% of the census tracts. However, 9% of census tracts had high barriers to water affordability but low barriers to water access and quality, meaning that citizens could access high-quality water, but it was relatively more expensive (data not shown). Co-occurrences of high or low barriers across FEWS were also infrequent (Figure 3-b). Barriers to affordability of FEWS co-occurred most often and exclusively in parallel; that is, census tracts frequently had all high (14%) or all low (11%) barriers to FEWS affordability.

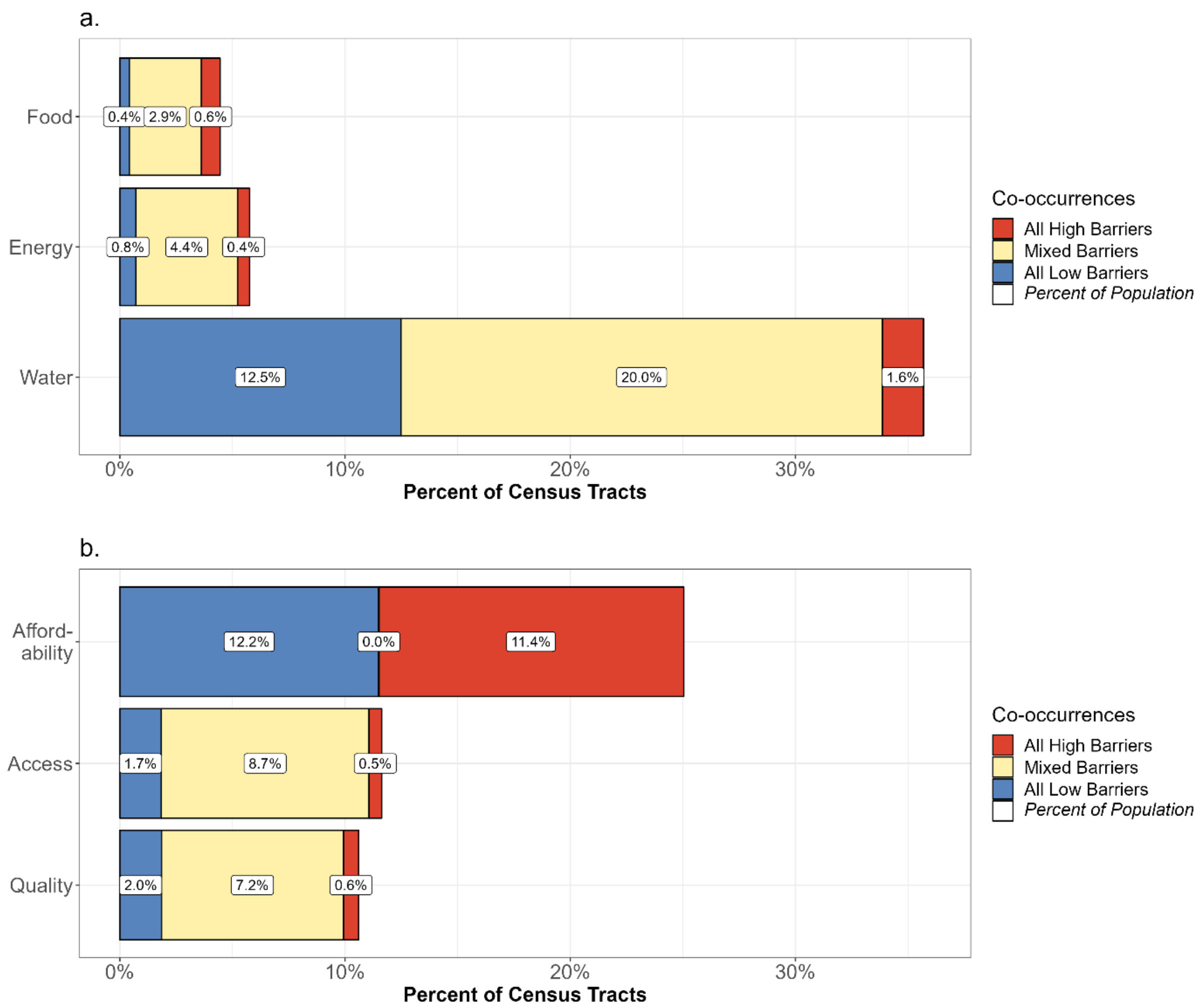

Figure 3: Percentage of census tracts with co-occurrences (a) within each food, energy, or water system and (b) within each barrier to affordability, access, and quality. High Barriers = census tract in the bottom 20th percentile, indicating more barriers to equity in each system. Low Barriers = census tracts in the top 80th percentile, indicating less barriers to equity in each system. Mixed barriers = some barriers were in the top 20th percentile and some barriers were in the bottom 20th percentile.

3.4 FEWS Equity Barriers Index

The FEWS Equity Barriers Index combines metrics associated with affordability, access, and quality barriers to FEWS resources, as well as community resilience to climate change (Figure 4). Combining nationwide metrics provides a snapshot of barriers to FEWS resources and suggests areas for stakeholder engagement and targeted investment. While FEWS are biophysically interconnected and require consideration of the whole nexus, maps detailing index values for individual FEW systems also offer insights into patterns and trends across the US.

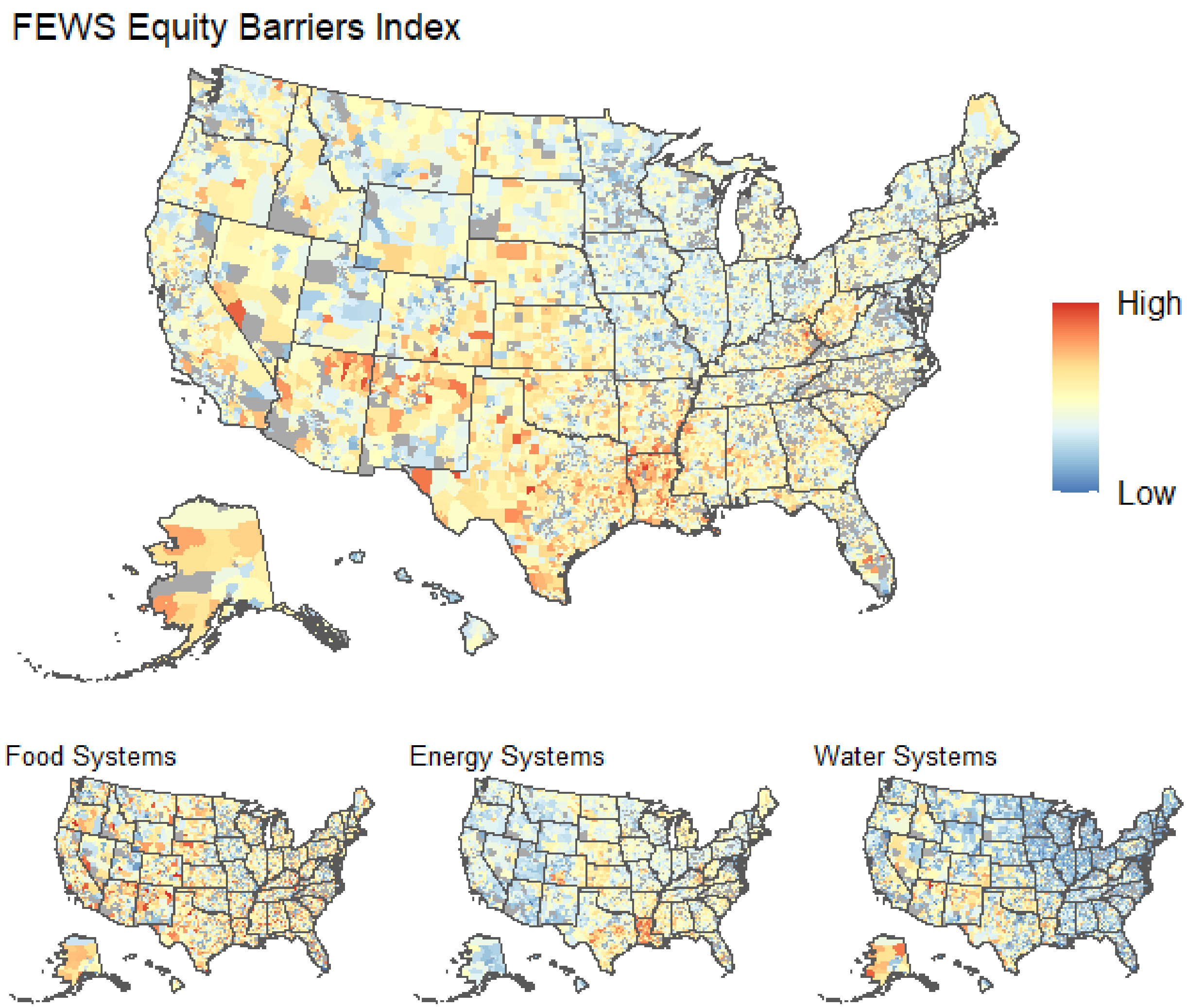

Figure 4: Values of the FEWS Equity Barriers Index and individual F, E, W systems in the US. Higher values represent higher barriers to FEWS equity. Grey areas indicate missing data.

To this point, higher FEWS Index values in the Southwestern US were primarily influenced by considerably high barriers to water resources. Meanwhile, the influence of energy systems on the FEWS Equity Barriers Index is notable along the Gulf Coast, particularly in states like Louisiana, Florida, and Texas. In Northern states where energy for heating during winter months is essential, we expected higher energy costs to drive higher affordability barriers; yet, the energy system index showed higher barriers to affordability and quality in Southern states (Figures 1 and 4). Food systems show fewer regional trends that influence the FEWS Equity Barriers Index. Compared to energy systems (i.e., Western states have lower barriers) and water systems (i.e., where Eastern states have lower barriers), food barriers vary throughout the US (Figures 1 and 4).

The FEWS Equity Barriers Index had a moderate positive spatial autocorrelation, with a Moran's I value of 0.37 (Figure 5). Areas of low barriers to FEWS resources were clustered primarily in Hawaii, the Midwest, and some Northern states. Areas of high barriers were clustered in Alaska, the Southern US, and some Western states. An interesting note is that while the index had a positive spatial autocorrelation, there were few co-occurrences between barriers in the same census tract (Figure 3).

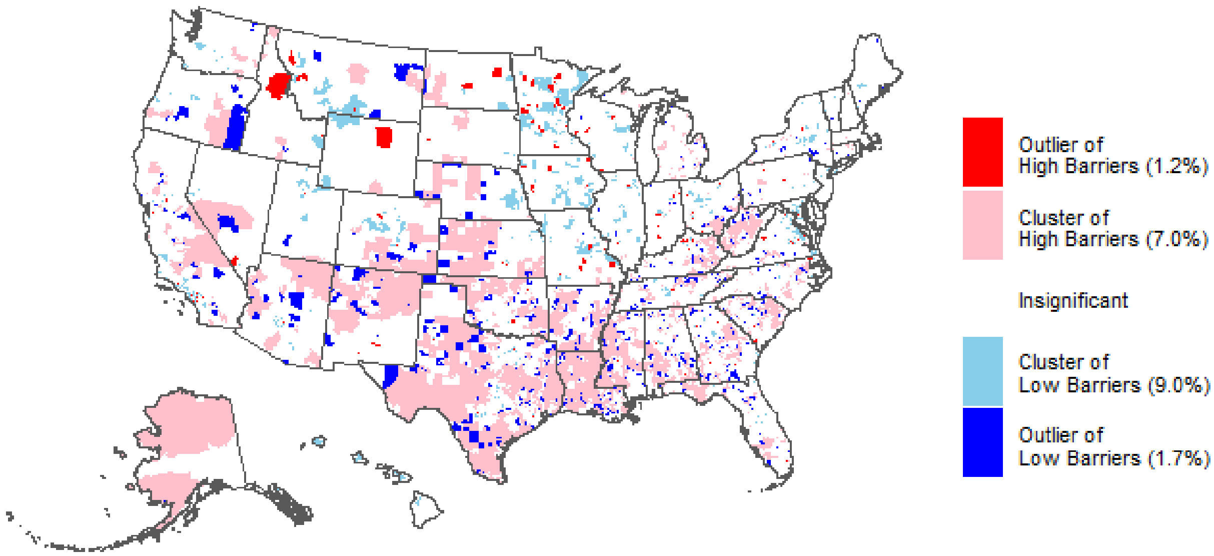

Figure 5: Spatial clustering of the FEWS Equity Barriers Index, as determined by Moran's I and Local Indicators of Spatial Autocorrelation (LISA). Clustering census tracts indicate large groups of census tracts with similarly high/low values, while an outlier census tract is dissimilar to neighboring census tracts. Insignificant census tracts are neither similar nor dissimilar to their neighbors, as determined by the LISA analysis. Values in parentheses indicate the percent of the US population in each cluster type.

4 Discussion

4.1 Variation of FEWS Equity Barriers by State

Affordability barriers across FEWS were predominately observed in states with below-average median incomes, suggesting that these barriers stem from financial disadvantages rather than high costs of living (US Census Bureau, 2020). Indeed, Teodoro and Saywitz (2020) found regional trends showing worse affordability potential in the South versus other areas of the US. Further, many other researchers have observed high barriers to energy affordability throughout the South, with some studies indicating that the use of electric rather than natural gas heating may exacerbate affordability issues for low-income households in Southeastern states with climates that require substantial heating and cooling (M. A. Brown et al., 2020b).

Our findings on population-weighted food access barriers differ from the US Department of Agriculture (USDA) food access reporting, where South Dakota had the highest population share in low access census tracts (Rhone et al., 2019). It is difficult to compare our findings with the USDA report because we considered all census tracts with data rather than the USDA's method of sorting by a binary measure of low access. Additionally, food access is commonly contextualized by looking at income level in addition to distance from grocers; low-income households may have outsized difficulty getting to a distant grocery store because they do not have access to a vehicle (Ver Ploeg et al., 2015). Energy and water access barriers were highest in Louisiana and Alaska, respectively. Louisiana is vulnerable to natural hazards, including hurricanes, flooding, storms, and extreme temperatures; furthermore, climate change is increasing the number of outages caused by extreme weather resulting in the highest number of outage hours in the US (Climate Central, 2022; Do et al., 2023). Many studies have confirmed the lack of access to water infrastructure in Alaska, with causes attributed to unique environmental and social conditions along with a lack of financial resources (Brown et al., 2022; Penn et al., 2017; Spearing et al., 2022).

The higher energy quality barriers in the Northern US are related to higher energy use in Northern states with cold climates. While higher energy barriers in the Northern US relate primarily to biophysical factors such as climate and weather, sociopolitical factors can determine the actual impact on people living there. For example, weatherization programs reduce energy use and costs to households in cold climates by insulating, sealing, and repairing residential structures (Tonn et al., 2023, 2018). Furthermore, many states take advantage of federal funding to offer assistance for energy-efficient appliance purchases and home repairs to low socioeconomic status households (American Council for an Energy-Efficient Economy, 2017; Cluett et al., 2016). Policies and programs that help households overcome energy barriers were not captured in our analysis but should be considered when engaging stakeholders at a local level to gain additional context.

Climate vulnerabilities in Southwestern states can be linked to natural hazards, including drought, heat waves, fires, and earthquakes (Zuzak et al., 2022). Along the Gulf Coast, natural hazards such as hurricanes, extreme storms, flooding, and tornados make states like Texas, Mississippi, Alabama, Georgia, and Florida relatively vulnerable (Zuzak et al., 2022). Natural hazards are not the only determinant of climate vulnerability; sociocultural, economic, and institutional factors are considered along with the condition of the built environment and community capacity to determine overall climate resilience or vulnerability (Cutter et al., 2014). Thus, barriers to climate resilience offer insights into the relationship between biophysical and sociopolitical factors that influence outcomes. For example, Tee Lewis et al. (2023) found six distinct geographic groupings of census tracts across the US with similar climate vulnerability scores driven by environmental, social, and built environment factors. In this way, climate resilience can be a good gauge of current and future FEWS barriers by quantifying systematic risk.

4.2 Spatial Analysis

The lack of spatial clustering in affordability data could be caused by the normalization of cost data by the median household income in each census tract. Large disparities in household income can exist between neighboring census tracts or even neighboring houses (Weinberg, 2011), which reduces the likelihood of spatial clustering. However, higher costs of living (such as housing, food, water, energy, etc.) are associated with higher median income, suggesting that the two may have a dampening effect on each other (Bauer et al., 2018).

Although energy companies typically operate on a much smaller extent to deliver power to buildings (i.e., one to a few companies per state; Edison Electric Institute, 2023), these connections are nested within a larger grid network connecting multiple states (US Environmental Protection Agency, 2023). With such a large regionally connected energy grid, wide-reaching energy disruptions are more likely. Further, factors that contribute to increased energy consumption intensity (energy quality) or outage durations (energy access) are most often climate- or weather-related and occur regionally. However, even in systems primarily influenced by environmental factors, socioeconomic factors can still significantly impact outcomes. For example, Tong et al. (2021) found census blocks with a higher proportion of people of color had higher energy use intensity, which has been linked to historically discriminatory housing policies that result in older housing stock and lower rates of home ownership (Goldstein et al., 2022). Adding to this disparity, higher energy use in low-income homes is related to the high initial cost of having an energy-efficient household (Pivo, 2014). Meanwhile, energy costs are based on the distribution company and usage levels, leading to a stronger tie to the built environment (i.e., building efficiency and energy grid) as well as the natural environment (i.e., climate), which influences demand.

Spatial analysis revealed varying patterns across the different FEWS metrics. The community resilience metric was highly spatially clustered (Moran's I = 0.67), which may be attributed to its reliance on social measures such as the demographic makeup, financial well-being, and sociocultural properties. Additionally, localized infrastructure and institutional factors within a community could contribute to this relatively high level of spatial clustering (University of South Carolina - Hazards & Vulnerability Research Institute, 2015). In contrast, water quality barriers exhibited a lack of clear spatial trends. This absence of pattern could be related to how Community Water Systems (CWS) receive violation points, which are not entirely based on the quality of water but also on the quality of monitoring and communication (US Environmental Protection Agency, 2023). Further, common treatments for contaminants vary by CWS; that is, not all CWS treat for all contaminants. Additionally, we could not account for water quality in private well systems used in many rural areas that could influence the spatial trends related to water quality. Other researchers have observed the lack of data about private well water quality and emphasized the need for further study (Allaire et al., 2018; Marcillo & Krometis, 2019).

4.3 Co-Occurrences of Barriers

The lack of co-occurrences in food and energy systems suggests that some barriers to food and energy resources are less related to location, possibly due to the dispersed nature of food and energy systems compared to water systems (Stone et al., 2023). Meanwhile, low barriers to water access were likely due to the distribution of barriers to water, which was highly skewed towards 0 or low barriers to both water access and water quality (data not shown).

The census tracts with high barriers to affordability of resources in all three FEWS are either financially disadvantaged due to lower income or located in areas with higher costs of living. In our analysis, census tracts with high affordability barriers had lower median incomes–just over half (55%) of the overall average median income across all US census tracts. Food, energy, and water costs in these tracts were also lower–12% less than the US average, indicating that median income has a greater effect on affordability barriers. Census tracts with low barriers to FEWS affordability averaged almost seven times larger in geographic area than census tracts with high barriers to FEWS affordability. This result suggests rural areas have lower barriers to affordability because the similar population counts in census tracts indicate large tracts are less densely populated. In this analysis, we did not delve into the disparities between urban and rural areas, but it would be valuable to investigate this contrast in future research.

Even though affordability indicators were not highly spatially correlated (Moran's I < 0.3; Figure 2), they often co-occurred in the same census tracts and followed the same trend (i.e., high affordability barriers co-occurred with other high affordability barriers). The trend of co-occurrences with a lack of spatial clustering could suggest that affordability barriers are caused by more systemic issues brought on by local sociopolitical factors associated with governance rather than biophysical factors such as climate and geology. To this point, a literature review of low-income households in the Southern US found that both location and socioeconomic status impacted energy burden, with rural areas and marginalized communities experiencing the greatest energy burden due in part to older housing stock, energy source, and efficiency policies and programs that are not accessible to low-income people (M. A. Brown et al., 2020a). In the context of the COVID-19 pandemic, food system inequities reinforced health inequities: Black and Indigenous communities and people of color in the US disproportionately experienced both increased food insecurity and hospitalization (Klassen and Murphy, 2020). Several studies assessing affordability highlight the importance of a nuanced relationship between economic, social, and demographic factors that can increase food, energy, and water resource vulnerability (Cardoso and Wichman, 2022; Doremus et al., 2022; Horst et al., 2016).

4.4 FEWS Equity Barriers Index

The FEWS Equity Barriers Index was heavily influenced by one system in a few regions, such as high barriers to water resources in the Southwestern US. Droughts in the Western US have heightened water scarcity, leading to increased costs, treatment challenges, and conflicts over water rights and allocation that directly affect affordability, access, and quality (McKinney and Thorson, 2015). Agricultural production accounts for the majority of water usage in the Western US (Schaible and Aillery, 2017) and contributes to the contamination of water resources, particularly by increasing nitrate concentrations (Schaider et al., 2019), which could increase water costs or degrade water quality. Extended droughts in the Western US are becoming more frequent and severe due to climate, causing an increased reliance on groundwater for irrigation that further strains water supplies (Balting et al., 2021). Studies of water system barriers in this region also found similar trends that tie water insecurity to increased drought, temperatures, and deteriorating physical water infrastructure (Mullin, 2020). Furthering the strain on water supplies, climate change-induced wildfires compromise traditional source water from snowmelt in forested mountain watersheds (Barnard et al., 2023). Water access insecurity is nuanced in the US context, with 50% of the population with incomplete plumbing living in highly urbanized spaces that disproportionately hurt low-income communities and people of color (Meehan et al., 2020). These diverse pressures on water resources underscore the urgent need for integrated management and governance to ensure sustainable and equitable access to FEWS resources.

Energy barriers to access were predictably higher in these areas where natural disasters (e.g., tornados, hurricanes) that can cause outages are more prominent (Burga, 2022). The high barriers to energy affordability and quality in Southern states rather than Northern states could be partially explained by the older housing stock in the South or by the use of natural gas for heating in the North, which is often less expensive than electric heating and cooling in the South (M. A. Brown et al., 2020a). In addition, lack of access to heat in Northern winter climates has more severe consequences on housing stock (e.g., burst water pipes) than lack of access to cooling in the summer. However, low-income communities and people of color in the South face increasing health risks from lack of access to air conditioning due to extreme temperatures caused by climate change (Gutierrez and LePrevost, 2016; Hsu et al., 2021; Wilson, 2020).

The lack of regionality in food systems may be due to the food system metrics available because lack of access due to spatial limitations (i.e., food deserts) in the US is common in rural areas regardless of region (Horst et al., 2016). Likewise, food system affordability and quality barriers (based on the proportion of healthy food retailers) tend to cluster in areas with higher population and median income, meaning that racial and socioeconomic barriers can limit food access within cities on a highly localized basis, with less variability at the regional scale (Crowe et al., 2018; Sullivan, 2014).

The FEWS Equity Barriers Index has some important limitations in the context of indigenous FEWS resources and land use. For example, Alaska was found to have consistently high barriers, particularly related to food and water resources (Figure 4). Lack of complete plumbing is more prevalent in Alaska than in any other state (Antrobus et al., 2017), and water quality violations at the CWS are high for a large portion of the population as well (Marino et al., 2009). The lack of safe, reliable, and accessible water systems is a well-known issue in Alaska, stemming from complex sociopolitical and natural challenges (Spearing et al., 2022). Small, rural communities located in harsh arctic environments face difficulties related to funding, building, maintaining, and operating piped water systems that are prone to failure during winter months (Cozzetto et al., 2013; Hickel et al., 2018; Thomas et al., 2016). However, work by Schmidt et al. (2022) in rural areas of Alaska found that residents reported high FEWS security, particularly in food and water resources. One explanation for this contrast may be that our indicators did not capture traditional sources of food, energy, and water collected from the local environment; that is, many of the residents interviewed by Schmidt et al. (2022) reported gathering their own FEWS resources rather than relying on contemporary infrastructure. The data we used in the analysis may also obscure intricacies related to energy systems, as we were unable to include information about energy obtained from traditional sources such as firewood. These data availability considerations likely apply to other states and regions in the US, especially rural areas.

Clusters of high barriers suggest that barriers could be influenced by the local natural environment and sociopolitical factors. We would expect census tracts with co-occurrences to have an inflated or deflated index value, depending on whether the co-occurrences were of high or low barriers. Likewise, we would expect a moderate index value in census tracts that did not contain co-occurrences. The positive spatial autocorrelation observed in the index emphasizes the importance of considering local factors related to built, natural, and sociocultural environments.

4.5 Significance and uses for the FEWS Equity Barriers Index

In this study, we identified census tracts in the US where residents face greater barriers to FEWS resources. Residents in these census tracts may be more vulnerable to future climate change impacts on FEWS. For example, a recent US Environmental Protection Agency (2021) report found that many socially vulnerable groups (identified based on income, race, ethnicity, education level, and age) were disproportionately impacted by climate change ranging from direct effects on FEWS (e.g., inland and coastal flooding) to indirect (e.g., extreme temperatures, air quality and health). Thus, increasing resilience by modifying the built environment, such as weatherization of buildings and the power grid, could produce co-benefits for health and equity under a changing climate (Vörösmarty et al., 2023b; Younger et al., 2008). The FEWS Equity Barriers Index combines key physical and social barriers for equity and FEWS in one useful metric, creating opportunities to understand how FEWS interacts with social equity, which could support targeted climate-smart investments in critical FEWS infrastructure.

Many indices have been developed to describe socioeconomic or demographic inequities by comparing geographic regions (e.g., countries or cities), for example, the Climate & Economic Justice Screening Tool (CEJST; Executive Office of the President of the United States: Council on Environmental Quality, 2022) and the Energy Justice Dashboard (US Department of Energy: Office of Economic Impact & Diversity, 2023). These tools aim to identify "disadvantaged communities that are marginalized, underserved, and overburdened by pollution" (The Biden Administration, 2023). While some data sources and themes in the FEWS Equity Barriers Index are similar to those in the Energy Justice Dashboard and CEJST, our index can identify barriers to FEWS resources and support diverse stakeholder-engaged conversations and decision-making. We did not include socioeconomic or demographic variables in our index; rather, we explored critical co-occurrences among interconnected systems to highlight equity concerns specific to the FEWS context. This study can thus serve as a guide for future FEWS researchers and stakeholders across governmental or geographic scales to explore potential barriers. The maps provided could also help government officials and decision-makers to identify locations where investments should be made to either increase equity in these systems or provide services to assist more vulnerable or at-risk populations.

A recent review of the literature found that a growing number of FEWS studies have used stakeholder-engaged mapping to support effective governance and confront critical FEWS challenges across governmental scales (Tye et al., 2022). However, these efforts often include only stakeholders who are current decision-makers and, thus, reflect current power structures (G. Brown et al., 2020). This type of participatory mapping is a promising approach that could engage stakeholders and support decision-making if implemented with an equity lens to enhance institutional and interpersonal trust (Chambers, 2006; Garcia-Martin et al., 2017). The maps of current barriers to FEWS resources at the census tract scale developed in this study could support this effort by identifying where to begin stakeholder engagement and the critical FEWS equity barriers necessitating investments in these areas. Given that FEWS decision-making involves both socio-cultural and biophysical components (Garcia-Martin et al., 2017), our digital maps would be most effective when used to enhance place-based conversations about community planning. These discussions should involve decision-makers and those most impacted by FEWS barriers, using co-creation and participatory methods similar to those found within sustainability science, natural resource management, and agroecology literature (Busse et al. 2023; Hakkarainen et al., 2022; Lopez-García et al., 2021).

4.6 Limitations and Data Needs

The availability and quality of nationwide data limits this and similar analyses. Detailed socioeconomic and demographic data take time and care to collect. Data collection at the national scale requires substantial funding and organizational efforts, often possible only through government support. Due to privacy and statistical accuracy concerns, most data were aggregated at coarser resolutions by the data collection agencies (e.g., the US Census Bureau). Inconsistent metrics and lack of high-resolution (e.g., census tract) data can make it challenging to create tools to support FEWS decision-making (M. A. Brown et al., 2020a). Ideally, all metrics used in this analysis would be collected simultaneously to best represent FEWS resource provisioning at a snapshot in time. We attempted to find the most reliable and accurate data sources from as similar years as possible, with most datasets collected within a three-year timespan (i.e., 2020-2023), except for the 2012 food quality data. Other FEWS nexus researchers have encountered similar issues in obtaining relevant data across geographic regions and scales, indicating the need for improved collection and aggregation of national FEWS data (Khan et al., 2022; Yadav et al., 2021).

Many data sources for identifying current barriers to affordable, accessible, and high-quality FEWS were difficult to locate at a national scope or from reputable sources. Food system barrier data were particularly challenging to obtain, likely due to the complex and international nature of food systems, alongside the difficulty of collecting data within a free-market context (Stone et al., 2023). The large proportion of missing food data (25% and 36% in access and quality, respectively) likely dampened the spatial trends found in our analysis. This dampening effect would occur because clustering analysis is based on neighboring census tracts, and missing data reduces the number of neighbors for affected tracts (Anselin, 1995). We used food deserts as the indicator for spatial access to food , although this measure alone is not a comprehensive representation of food insecurity (Taylor & Ard, 2015). No alternative measure capturing the multiple dimensions of food access was available with the necessary spatial orientation and coverage for our study. Improving FEWS equity analyses requires the development of more comprehensive food access and security indicators that are rooted in principles of social equity, applicable at the national scale, and sensitive to local contexts (ver Ploeg et al., 2015).

Environmental and social system interactions further complicate identifying useful FEWS barrier metrics. For example, food deserts are less correlated to diet-related health disparities than to income and race (Brinkley et al., 2017). The energy quality barrier was similarly challenging due to the lack of energy efficiency data at the household level. Energy use and costs are often greater for low-income or renting households without the means (or permission) to increase the energy efficiency of their home (Pivo, 2014) or appliances (M. A. Brown et al., 2020a). Although the ideal energy quality barrier metric would be a comprehensive measure of household energy efficiency, we used the best available option – temperature regulation on a square foot basis.

The FEWS Equity Barriers Index used equal weighting of nine FEWS barriers related to affordability, access, and quality, including one additional barrier to climate resilience. Index weights are generally assigned one of four ways: i) equal weighting (as done in this study), ii) weights based on statistical analyses such as principal component analysis, iii) weight assignment based on the results of a multi-criteria decision-making process, and iv) participatory selection by surveying experts or stakeholders (Moreira et al., 2023). We chose to use equal weights to account for the interconnections within the FEWS nexus and avoid biasing the result to any particular system or barrier type. Exploring different weighting schemes, particularly stakeholder-engaged participatory weighting, could support regionally specific analyses for effective governance in the face of climate change and increased human population (Carrier et al., 2016; Heckert & Rosan, 2016; Albrecht & Ramasubramanian, 2004).

Though not included in our study, sociocultural barriers are another critical form of inequity in FEWS that can involve personal preferences, cultural norms, and household dynamics (Stone et al., 2023). These barriers are difficult to incorporate because they require collecting qualitative or interview data using place-based and mixed methods that are more conducive to a narrower scope and geographic scale (Dean and Sharkey, 2011; Hoolohan et al., 2018). One avenue for future work is to use our FEWS Equity Barriers Index map as a starting point to engage stakeholders in developing methods and measures for incorporating place-based sociocultural FEWS barriers. Combining our index with such measures could be useful for FEWS decision-making and planning, particularly by coordinating with decision-makers to increase climate change resiliency.

5 Conclusion

FEWS resources are critical to human health and well-being, but barriers to quality resources exist for many populations across the US. Inequities can be highly localized, with some census tracts having more barriers to FEWS than others. Our previous work highlighted the need for comprehensive tools to assess social equity in FEWS (Stone et al., 2023). FEWS are inherently tied to place, necessitating an ability to consider regional, local, and place-based elements (Garcia and You, 2016). Our analysis at the census tract scale identifies inequities within communities and provides an opportunity to make nationwide assessments that can inform FEWS governance. Using equity metrics related to affordability, access, quality, and climate risk, we developed a spatial index to understand the current condition of equitable distribution of FEWS within the US.

Government agencies and decision-makers at local, regional, state, and federal levels should consider barriers and potential equity implications when administering FEWS resources. The FEWS Equity Barriers Index can support the comparison of entities across different geographical locations, as was shown in this study. These comparisons could act as a catalyst for stakeholder-engaged conversations about best practices that connect biophysical FEWS to social equity and well-being. Future work should focus on co-producing specific pathways to reduce inequitable barriers in FEWS, especially those that can be exacerbated by climate change or for census tracts with high barriers. Local community engaged analyses (i.e., in a city or county) could also help to identify barriers that are difficult to measure nationally, such as social and cultural preferences, perceptions, and experiences. Regarding affordability, our work suggests that issues were systemic and caused by local sociopolitical factors, not solely the naturally existing environment. These systemic issues should be addressed to ensure fair and just FEWS access both now and in the future.

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