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RESEARCH ARTICLE

Measuring resilience in national food systems using "food systems resilience score"

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Abstract

Achieving Zero Hunger by 2030, a United Nations Sustainable Development Goal, requires resilient food systems capable of securely feeding billions. This article introduces the Food Systems Resilience Score (FSRS), a novel framework that adapts a proven resilience measurement approach to the context of food systems. The FSRS builds on the success of the Community Flood Resilience Measurement Tool, which has been used in over 110 communities, by applying its five capitals (natural, human, social, financial, and manufactured) and four qualities (robustness, redundancy, resourcefulness, and rapidity) framework to food systems. We define food system resilience as the capacity to ensure adequate, appropriate, and accessible food supply to all, despite various disturbances and unforeseen disruptions. The FSRS measures resilience across multiple dimensions using carefully selected existing indicators, ensuring broad applicability and comparability. Our methodology includes rigorous technical validation to ensure reliability, including optimal coverage analysis, stability checks, and sensitivity testing. By providing standardized metrics and a comprehensive assessment of food system resilience, this framework not only advances research but also equips policymakers with valuable tools for effective interventions. The FSRS enables comparative analysis between countries and temporal tracking of resilience changes, facilitating targeted strategies to build and maintain resilient national food systems. This work contributes to the global effort toward long-term food security and sustainability.

Policy Significance Statement

The Food Systems Resilience Score (FSRS) offers a comprehensive approach to assessing national food system resilience (FSR), building on a proven model of five capitals and four resilience qualities. This multidimensional tool offers powerful insights for policymakers not only to assess and enhance resilience but also to quantify current states and anticipate responses to future shocks. Through comparative analysis and tracking over time, the FSRS allows for areas of intervention, identification, and assessment of strategy impacts. While focused at a national level, the FSRS lays the groundwork for regional and localized applications. The FSRS offers policymakers a standardized yet flexible framework for building effective and context-specific strategies, which may assist in contributing to achieving global food security and the UN Sustainable Development Goal of Zero Hunger by 2030.

This research article was awarded Open Data and Open Materials badges for transparent practices. See the Data Availability Statement for details.

1. Introduction

Recently, the concept of resilience has been widely accepted as an enabler for long-term sustainable growth. Amidst the growing challenge of feeding billions of people in a food-secure way, the global food system has also embraced this concept to achieve the United Nations Sustainable Development Goal of Zero Hunger by 2030 (Ingram, 2011; Nutrition, 2017). Recent reports indicate that progress toward this goal has stalled, with the number of undernourished people rising to 828 million in 2021 (FAO, IFAD, UNICEF, WFP and WHO, 2022). Initially envisioned as the dynamic capacity of the 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 (Tendall et al., 2015), the concept of food system resilience has evolved constantly (KC et al., 2024). Consequently, the way the resilience of food systems is measured has also changed over time. Several development organizations have introduced various aggregated scoring systems to measure the level of FSR and/or their relevant concepts, such as food security. The list of existing measurement systems includes Resilience Index Measurement and Analysis (Food and Agriculture Organization (FAO)) (RIMA-II, FAO, 2016), OXFAM (Hughes and Bushell, 2013), United Nations Development Programs (UNDP) (UNDP, 2013), Organization for Economic Co-operation and Development (OECD) (OECD, 2014), United States Agency for International Development (Frankenberger et al., 2013), and Global Food Security Index (GFSI) (Economist Intelligence Unit, 2015). More recent efforts have also emerged, such as the Food Systems Dashboard (Fanzo et al., 2020), that aim to provide comprehensive assessments of food system performance and resilience. While these existing systems provide valuable insights, there is a critical gap in the field: the need for an operationalizable framework specifically designed to measure FSR. Building a consistent aggregated scoring system to measure resilience in a complex ecosystem of food systems across countries where data infrastructure and technology can vary significantly is a nontrivial task and suffers from various methodological and conceptual challenges. These challenges are further compounded by the increasing complexity and interconnectedness of global food systems (Kummu et al., 2020).

Serfilippi and Ramnath (2018) highlighted a lack of consensus and subsequent absence of common language and standardized metrics in the measurement of FSR, despite increased awareness among development practitioners. Similarly, a review of the sustainability indicators of food systems by Bene et al. (2019) pointed to a group of factors, including the limited data availability for many countries, the lack of conceptual clarity on how the indicators are grouped, the technical issues of replication, the strong cross-correlation among indicators, and the sensitivity of the aggregated score in existing measurement systems, as bottlenecks in their effective utilization. There is also a need for resilience metrics that can capture both short-term shocks and long-term stressors affecting food systems (Herrera, 2017; Béné et al., 2021). The need to measure and understand the responses of food systems to shocks and adverse events has gained increased significance in light of recent major disruptions. The coronavirus disease 2019 pandemic and the Russia–Ukraine crisis have underscored the importance of resilience in global food systems (Dyson et al., 2023; Rabbi et al., 2023; El Bilali and Ben Hassen, 2024; Kvasha et al., 2024). These events have highlighted the vulnerability of food supply chains to unexpected shocks and emphasized the critical need for robust resilience measurement tools to inform policy and decision-making in the face of future challenges.

This study aims to address these methodological and conceptual issues by first operationally defining FSR and then systematically developing a composite score called the "Food Systems Resilience Score" (FSRS) to measure it on a national scale. The FSRS integrates multiple parameters from various disciplines into a single measurement tool, reflecting the interdisciplinary nature of food security and resilience. This approach allows for a comprehensive assessment of the resilience of food systems that captures the complex interactions between different aspects of the system.

We operationally define FSR as "*the capacity of food systems to ensure adequate, appropriate, and accessible food supply to all in the face of various disturbances and unforeseen disruptions. It achieves this across multiple dimensions—natural, human, social, financial, and manufactured capitals—through*

a robustness to withstand shocks, redundancy that retains functionality, resourcefulness to mobilize resources, and agility to meet goals swiftly."

The key concepts to this operational definition are the five capitals model of sustainability(DfID UK, 1999)—natural, human, social, financial, and manufactured—and four qualities of resilience (Bruneau and Reinhorn, 2006)—robustness, redundancy, resourcefulness, and rapidity (4Rs). The five-capital framework was adopted, as the concept of capitals helps measure a stock at any stage (before and after a shock). Such an ability to measure stocks can also help assess and forecast the vulnerability and potential responses of the system when exposed to any shocks, based on the initial conditions of the system. This model has been widely used to holistically capture the assets and capacities that enable a system to achieve the goals of well-being, opportunity, and risk management. The framework can be applied both quantitatively and qualitatively to any country and at multiple scales. Additionally, sustainability and resilience are viewed as complementary concepts, with resilience being an enabler of sustainability. Adapting an established framework for sustainability can thus harness the benefits of the framework for resilience measurement that was realized previously in sustainability measurement. Similarly, the consideration of the four qualities of resilience defined by Bruneau and Reinhorn (2006) in our operational definition complements the possible shortcomings of a capital-level resilience measurement in anticipating the performance of food systems when exposed to uncertain risks and opportunities. Our framework, based on the five capitals and four qualities (4Rs), aligns with contemporary resilience concepts, including aspects of the One Health approach. The concept of One Health emphasizes the interconnectedness of human, animal, and environmental health (Zinsstag et al., 2011), which is reflected in our holistic approach in different capitals. Moreover, our 4R framework inherently captures the five aspects of resilience often discussed in the One Health literature: threshold, coping, recovery, adaptive, and transformative capacities (Béné et al., 2012). Robustness relates to threshold capacity, redundancy to coping capacity, resourcefulness to adaptive and transformative capacities, and rapidity to recovery capacity. This alignment allows our framework to assess the complex interactions within food systems that contribute to overall resilience, reflecting the interdisciplinary nature of food security and current theoretical approaches in resilience assessment. One of the established works of literature that uses the complementary combination of these two concepts of capital and qualities is the Community Flood Resilience Measurement Tool (Keating et al., 2017) which operationally defines and measures community resilience against floods.

The composite score, termed FSRS, is built on the foundation of a rigorous systematic review of peer-reviewed academic articles (KC et al., 2024) to overcome consistency- and robustness-related issues. The factors, highly relevant to resilience thinking in food systems, underwent expert consultation before adopting the proven combination of capital and the qualities of resilience. After the classification of the relevant variables, the closest existing indicators were sought out. The use of existing indicators ensures the inclusion of a maximum number of countries, thereby overcoming the issue of representation in the score. We also present a technical validation of the score with a series of tests that include a stability check, optimal coverage, comparison against existing systems, and a sensitivity test to address any associated technical issues.

This study builds on an already-tested tool (the Community Flood Measurement Tool) (Keating et al., 2017) that has been used in more than 110 communities, in complex food systems where resilience measurement has remained vague. By adapting this proven framework to the context of food systems, we aim to provide a robust and operationalizable approach to measuring FSR at a national level.

Our work contributes to the growing body of literature on FSR by:

1. Providing a standardized, yet flexible, framework for assessing FSR at a national level.
2. Integrating multiple dimensions of resilience into a single comprehensive score.
3. Offering a tool for comparative analysis between countries, to track changes in resilience over time, and inform policy and decision-making.
4. Demonstrating the applicability of a proven resilience measurement approach to the complex domain of food systems.

The rest of the article is organized as follows. Section 2 presents the methods for FSRS starting from the operational definition of FSR, while Section 3 discusses the technical validation of FSRS. Section 4 includes discussions of key findings, policy implications, and limitations before concluding the article.

2. Methods

Our methods ensure both rigor and applicability, starting with the operationalization of resilience in food systems, building on an already tested model of five capitals and four qualities of resilience. This foundation, adapted from the successful Community Flood Resilience Measurement Tool (Keating et al., 2017), provides a sound conceptual framework to underpin our work. Following this, we conducted a systematic review of the literature and consultation with experts in order to identify relevant variables, employed existing indicators to achieve maximum coverage of countries, and carried out intensive statistical testing to address the issues of correlation, normality, normalization, and aggregation. This approach not only assures methodological rigor but also facilitates practical implementation across diverse national contexts. By replicating a successful model in the context of food systems, we have created a tool that is both theoretically grounded and operationally viable.

2.1. Operationally defining FSR

A design of any measurement system should have variables that can capture static and dynamic dimensions of what is being measured (Serfilippi and Ramnath, 2018). "Resilience" has been defined in several ways without an explicit consensus. Measuring resilience in complex food systems with several actors and components, along with their mutual interactions, is not a trivial task, as it can remain ambiguous without a solid foundation (McCubbin, 2001; Zurek et al., 2022). We envisioned the FSR as spanning different dimensions of capital and qualities, and aligning with how Constas et al. (2014) defined resilience as a combination of capacities to ensure adequate, appropriate, and accessible food supply to all in the face of various disturbances and unforeseen disruptions. We adapted the five capitals framework of sustainability (DfID, UK, 1999) to capture both static and dynamic aspects of resilience in food systems. Similarly, we used four qualities of resilience as described in Bruneau and Reinhorn (2006) and Cimellaro et al. (2010) to capture general principles that are thought to enhance resilience over time. Our vision of FSR under multiple dimensions of capital and quality not only identifies the enablers of resilience in food systems but also helps anticipate how food systems may perform when exposed to risks and opportunities. Along with these alignments, the demonstrated success of Keating et al. (2017) inspires our operational definition of FSR and, thus, the concepts of capitals and qualities of resilience underpin our operational definition and measurement of FSR. Please refer to Box 1 for definitions of FSR and its capitals and qualities.

2.2. Collecting variables and populating them with indicators

We employed a rigorous multistep process to select indicators for each of the five capitals and four qualities of our FSR framework:

1. Systematic literature review: We initially conducted a comprehensive review of academic peer-reviewed articles published in the last three decades, as detailed in KC et al. (2024). This review produced an extensive list of variables relevant to food security and FSR.
2. Expert consultation: The preliminary list of variables was then subjected to thorough discussion with food systems experts. This step ensured that we captured all relevant aspects of FSR and that our selection was comprehensive and up-to-date with current understanding in the field.
3. Indicator selection: To populate these variables with measurable indicators, we applied a strict protocol based on the following criteria:

Box 1. *Definitions of capitals and qualities of FSRs.*

FSR: The capacity of food systems across various dimensions—encompassing natural, human, social, financial, and manufactured capitals—that involves robustness to withstand shocks, redundancy to retain functioning, resourcefulness to mobilize resources, and rapidity to swiftly meet goals to ensure adequate, appropriate, and accessible food supply to all in the face of various disturbances and unforeseen disruptions.

Natural capital: Any stock or flow of energy and material that produces goods and services (DfID, UK, 1999).

Human capital: The capital that consists of people's health, knowledge, skills, and motivation (DfID, UK, 1999).

Social capital: The capital that concerns the formal and informal institutions and structures that help us maintain and develop human capital in partnership with others (DfID, UK, 1999).

Financial capital: The capital that plays an important role in our economy, enabling the other types of Capital to be owned and traded. However, unlike the other types, it has no real value itself but is representative of natural, human, social, or manufactured capital (DfID, UK, 1999).

Manufactured capital: The capital that comprises material goods or fixed assets that contribute to the production process rather than being the output itself (DfID, UK, 1999).

Robustness: The strength or ability of a system to withstand a shock (Bruneau and Reinhorn, 2006).

Redundancy: The extent to which a system can remain functional when exposed to a shock (functional diversity) (Bruneau and Reinhorn, 2006).

Resourcefulness: The capacity of a system to identify problems, establish priorities, and mobilize resources when exposed to a shock (Bruneau and Reinhorn, 2006).

Rapidity: The capacity to meet goals in a timely manner to avoid further disruption (Bruneau and Reinhorn, 2006).

- Existing: We included existing closely relevant indicators for the variables that were maintained by developmental organizations.
- Cross-correlation: We excluded the indicator that was closely correlated to another indicator already in the list and measured conceptually the same quantity.
- Global scale: We excluded the indicators that covered <50 countries.
- Regional: We excluded the indicators that were specific to a region and not relevant to a global scale.
- Freely available: We included the indicators that are freely and publicly available.
- Time period: We excluded the indicators that were not maintained for multiple recent years (after 2010).
- Comparability: We emphasized collecting the indicators that allow for comparability between countries.
- Clear methodology: We excluded the indicators for which the methodology for constructing the indicators was not clearly described.

4. Indicator categorization: After applying the protocol, we obtained a short list of 48 indicators. The indicators are listed in Table 1 and categorized under the five capitals and four qualities. Also included in the table are the source of the data for the indicator, the number of countries included, the nature of influence the indicator has on FSR, and the years for which the indicator data are available. Indicators with positive influence enhance FSR, while indicators with negative influence undermine the resilience. Out of 48 indicators, 9 are natural, 11 are human, 10 are social, 8 are financial, and 10 are manufactured. In the list, 14 indicators constitute robustness, 11 redundancy, 14 resourcefulness, and 9 rapidity.
5. Statistical validation: Finally, we conducted correlation checks (as shown in Figure 1) to ensure that the selected indicators were not redundant and each contributed unique information to the overall resilience score. The indicators in natural and manufactured capitals are less correlated compared to the indicators in human, social, and financial capitals.

Table 1. *All short-listed indicators, along with their source, influence, capital, qualities, number of countries covered, and range of years for which the indicators are maintained*

Indicator	Source	Influence	Capital	Qualities	#Countries	Years
Access to agricultural resources	GFSI, UN	Positive	Human	Redundancy	113	2012–2022
Access to diversified financial services	GFSI	Positive	Financial	Redundancy	113	2012–2022
Access to financial services	GFSI	Positive	Financial	Robustness	113	2012–2022
Adaptation of innovative technologies	GFSI	Positive	Manufactured	Redundancy	113	2012–2022
Agricultural GDP	FAO	Negative	Financial	Robustness	217	2000–2021
Agricultural production volatility	GFSI	Negative	Financial	Robustness	113	2012–2022
Agricultural R&D expenses	GFSI	Positive	Manufactured	Redundancy	113	2012–2022
Agricultural trade	GFSI	Positive	Financial	Resourcefulness	113	2012–2022
Agricultural water quality	GFSI	Positive	Natural	Robustness	113	2012–2022
Agricultural water quantity	GFSI	Positive	Natural	Robustness	113	2012–2022
Agricultural women empowerment	GFSI	Positive	Social	Redundancy	113	2012–2022
Armed conflict	GFSI	Negative	Social	Robustness	113	2012–2022
Biodiversity and habitat	EPI	Positive	Natural	Resourcefulness	180	2010–2022
Community organizations	GFSI	Positive	Social	Rapidity	113	2012–2022
Corruption	GFSI	Negative	Social	Resourcefulness	113	2012–2022
Crop storage facilities	GFSI	Positive	Manufactured	Rapidity	113	2012–2022
Dependency on chronic food aid	GFSI, OECD	Negative	Social	Rapidity	113	2012–2022
Disaster risk management	GFSI	Positive	Manufactured	Rapidity	113	2012–2022
Early warning measures	GFSI, CCAFS	Positive	Manufactured	Resourcefulness	113	2012–2022
Ecosystem services	EPI	Positive	Natural	Resourcefulness	180	2010–2022
Food dietary diversity	GFSI	Positive	Human	Redundancy	113	2012–2022
Food loss	GFSI, FAO	Negative	Human	Robustness	113	2012–2022
Food price volatility	GFSI, FAO	Negative	Financial	Robustness	113	2012–2022
Food safety	GFSI	Positive	Human	Resourcefulness	113	2012–2022
Food safety net programs	GFSI	Positive	Social	Rapidity	113	2012–2022
Food security policy commitment	GFSI	Positive	Social	Rapidity	113	2012–2022
Food supply sufficiency	GFSI, FAO	Positive	Human	Robustness	113	2012–2022
Forest change	GFSI, World Bank	Negative	Natural	Resourcefulness	113	2012–2022
Gender equality	UNDP	Positive	Social	Redundancy	195	1990–2021

(Continued)

Table 1. *Continued*

Indicator	Source	Influence	Capital	Qualities	#Countries	Years
Green gas emissions per capita	EPI	Negative	Natural	Resourcefulness	180	2010–2022
Income inequality	GFSI, UNDP	Negative	Financial	Robustness	113	2012–2022
Irrigation infrastructure	GFSI, FAO	Positive	Manufactured	Rapidity	235	1961–2020
KOFGI Globalization Index	KOFGI	Positive	Manufactured	Resourcefulness	204	2000–2019
Labor force participation rate	World Bank	Positive	Human	Redundancy	217	2000–2021
Land degradation	GFSI, UN	Negative	Natural	Resourcefulness	113	2012–2022
Literacy rate	World Bank	Positive	Human	Redundancy	217	200–2021
Micronutrient availability	GFSI, Global Nutrient Database	Positive	Human	Robustness	113	2012–2022
Natural hazard exposures	GFSI, ND-GAIN	Negative	Natural	Robustness	113	2012–2022
Nutritional standards	GFSI	Positive	Social	Resourcefulness	113	2012–2022
Per capita income	World Bank	Positive	Financial	Redundancy	217	2000–2020
Political stability risks	GFSI	Negative	Social	Resourcefulness	113	2012–2022
Population growth rate	World Bank	Negative	Human	Robustness	217	2000–2021
Poverty population	World Bank	Negative	Human	Redundancy	161	2010–2022
Protein quality	GFSI, WHO, USDA Nutrient database	Positive	Human	Robustness	113	2012–2022
Soil organic content	GFSI, FAO	Positive	Natural	Resourcefulness	113	2012–2022
Supply chain infrastructure	GFSI, World Bank	Positive	Manufactured	Rapidity	113	2012–2022
Sustainable agriculture	GFSI	Positive	Manufactured	Resourcefulness	113	2012–2022
Telecommunications	ITU	Positive	Manufactured	Rapidity	230	2000–2021

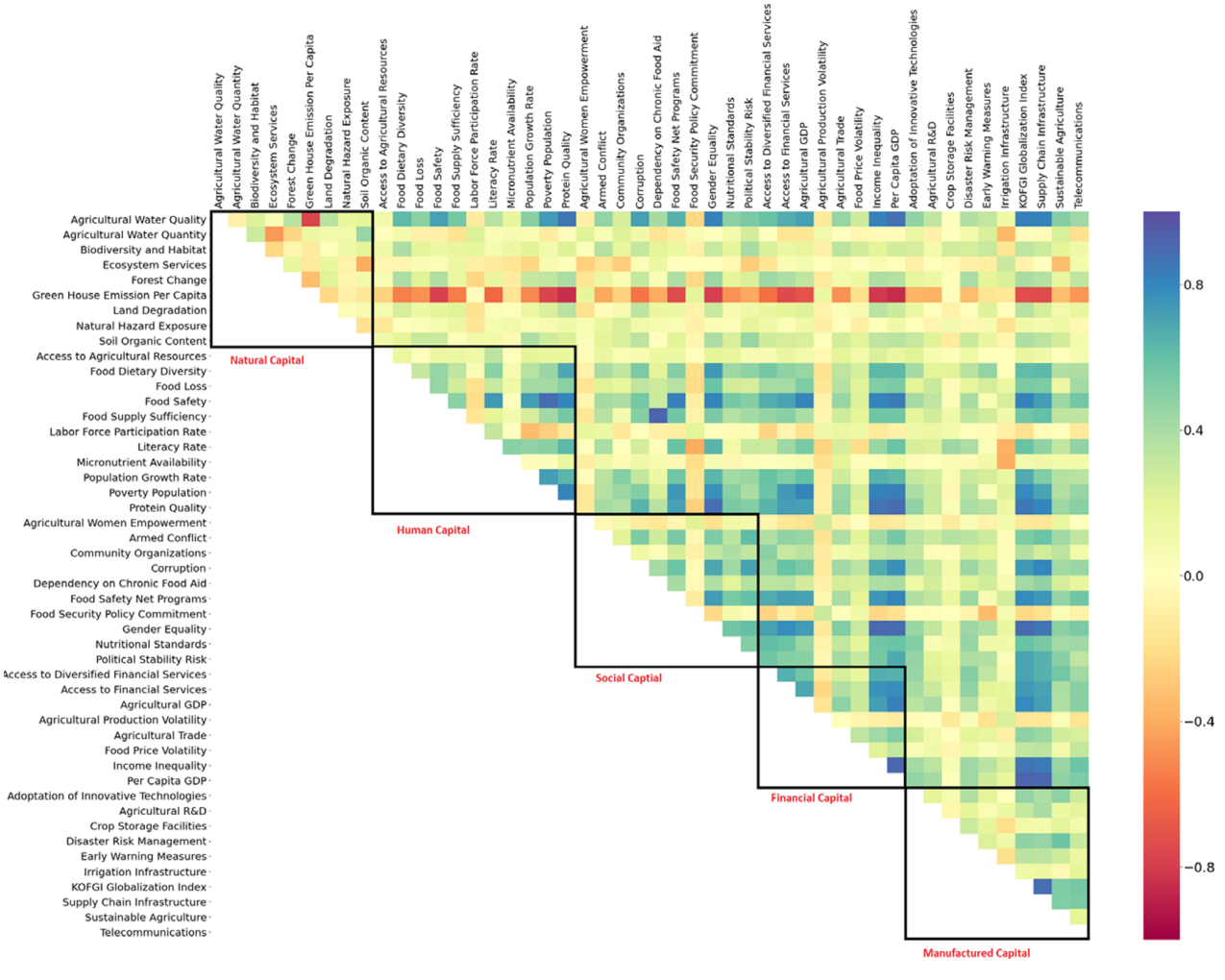

Figure 1. *Correlation check between the indicators in the FSRS framework. Natural and manufactured capitals have less intra-correlation, while human, social, and financial capitals have high intra-correlation.*

2.3. Computing the score

We applied the Box–Cox transformation to the most skewed indicators that had a magnitude of skewness above 2, that is, $|\text{skewness}(x)| > 2$. Such a transformation improves the normality of the distribution of the indicators and avoids potential issues arising from heteroskedastic data set distributions (Osborne, 2010). We then applied the normalization to the data sets using a standard minimum–maximum transformation with a [0,1] range. The data sets collected from existing score systems such as GFSI, Notre Dame Global Adaptation Initiative (ND-GAIN) (Chen et al., 2015), Human Development Index (HDI), and Environmental Performance Index (EPI) (Hsu and Zomer, 2014) are already normalized and hence do not require normalization. For other indicators, normalization was applied based on the nature of their influence on the resilience of food systems. The indicators with positive influence were normalized as follows:

$$x_{norm} = \frac{x - x_{min}}{x_{max} - xmin} \times 100 \tag{1}$$

The indicators with negative influence were normalized as follows.

$$x_{norm} = \frac{x_{max} - x}{x_{max} - xmin} \times 100 \tag{2}$$

We used the arithmetic aggregation method to calculate the score for capitals and qualities and the overall FSRS. An arithmetic aggregation method ensures equal weights for all indicators within the capitals, qualities, and ultimate FSRS. Since the scores for capitals and qualities are averaged to calculate the final FSRS, all the indicators do not have equal weights in the FSRS; indicators in the capitals or qualities with higher numbers of indicators have less weight than the indicators in the capital or quality with fewer indicators.

2.4. Data records

All indicators shortlisted are identified in the first column of Table 1. The standard definitions of these indicators are included in the Supplementary Information. Of the 48 indicators, 9 are natural, 11 are human, 10 are social, 8 are financial, and 10 are manufactured. The natural capital includes indicators covering several aspects of nature, such as water, biodiversity and ecosystems, forests, land, soil, greenhouse gas emissions, and natural hazard exposure. Similarly, the Human capital includes indicators covering the potential of human resources, such as access to agricultural resources, food sufficiency, diversity, loss and safety, labor, population growth, and availability and quality of micronutrients and proteins. Likewise, the Social Capital has indicators that encompass several social aspects, such as community organizations, food safety nets, food security policy, food aid, gender equality and participation, corruption, political stability, and conflict. The Financial Capital has indicators that cover access to financial services, income, production, prices, trade, and volatility. The Manufactured Capital includes indicators that cover innovative technologies, research and development, agricultural infrastructure and sustainability, disaster risk management and early warnings, and globalization. The Robustness comprises indicators representing access, availability, production, and loss of agricultural resources, such as agricultural Gross Domestic Product (GDP), food supply sufficiency, and access to financial services, while the Redundancy includes indicators such as agricultural R&D, agricultural women's empowerment, and food dietary diversity, which can offer some forms of functional diversity. The Resourcefulness includes indicators representing factors such as agricultural trade, food safety, forest change, biodiversity, and habitat that facilitate food system activities, while the Rapidity comprises indicators such as crop storage facilities, community organizations, and food safety net programs, which help in rapid recovery.

The second column of Table 1 shows the sources of the data on the indicators. The data source has the majority of data for indicators from UN organizations, such as the FAO, World Health Organization, and UNDP. Some existing composite indicator systems, such as the GFSI, KOFGI Globalization Index,

ND-GAIN, and EPI, were also used as data sources. Other data sources include the Global Nutrient Database, the World Bank, the International Telecommunications Union, Climate Change, Agriculture and Food Security (CCAFS), and OECD. All the datasets are freely and publicly available.

The third column indicates the influence of the indicator and the resulting level of FSR. A positive influence would mean that a higher score for the indicator corresponds to a higher level of resilience in the food system. For example, a high level of food dietary diversity, crop storage facilities, supply chain infrastructure, and food supply sufficiency would be indicative of a highly resilient food system, and hence these indicators are labeled to have a positive influence. In contrast, a negative influence implies that the higher the indicator score, the lower the level of FSR. For example, high levels of income inequality, food loss, land degradation, and corruption would be drivers of less resilient food systems.

The fourth and fifth columns contain information on the capitals and qualities of resilience to which the indicators belong, while the sixth column lists the total number of countries covered by each indicator. The last column shows the year range for which the data on the indicators is available.

3. Technical validation

Four different analyses that included optimal coverage, stability, sensitivity, and comparative were conducted to validate the robustness of the score. All analyses were conducted for the year 2019, as the most recent data available for indicators were most consistent in 2019.

3.1. Optimal coverage

One of the most challenging hurdles for our FSRS was finding the optimal balance between the number of countries covered and the number of indicators. Having fewer indicators meant more countries were covered in our composite score system, while having more indicators meant fewer countries were covered. We considered three decision criteria to address the optimality of the trade-off between the number of countries covered and the number of indicators. The three decision criteria are as follows:

- The number of countries added to the composite score system when the number of indicators is decreased by 1.
- The variability in the FSRS scores of the countries with complete data sets.
- The change in the ranks of the countries with complete datasets.

All these criteria were combined to form a normative optimization function, and the optimal coverage would minimize the function. Our initial screening was able to identify 23 countries with complete data sets for 48 indicators. We took this as the starting point for the application of the decision criteria for the optimal combination and calculated the values of the aggregated normative function. We found the combination of 44 indicators that covered 109 countries to be the optimal combination. Figure 2 shows the number of countries along with the number of indicators during the optimization of the coverage. Out of the 44 indicators, 8 belonged to natural, 10 to human, 10 to social, 8 to financial, and 8 to manufactured capital. The global map with the FSRS scores for this optimal combination is shown in Figure 3. Japan has the most resilient food system, followed by Norway, Switzerland, Finland, and the Netherlands in the list of top-5 ranked countries, while Yemen has the least resilient food system, with Haiti, DR Congo, Burundi, and Chad in the bottom 5.

3.2. Stability of score

There is a technical challenge of stability for any composite score system built using several indicators at a national scale. The technical challenge of stability in our framework refers to the situation when the scores for countries change substantially with any addition or deletion of indicators in the framework. The challenge is more severe when the number of indicators changes, causing the set of countries included to change significantly compared to the set included in the original set of indicators. The different sets of

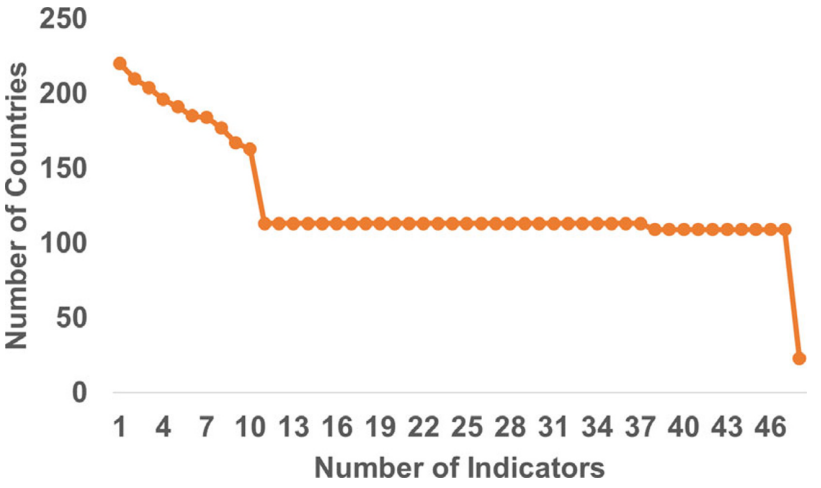

Figure 2. *Analysis of optimal coverage of FSRS. The subset of 1 indicator covered 220 countries, while the subset of 48 indicators covered only 26 countries.*

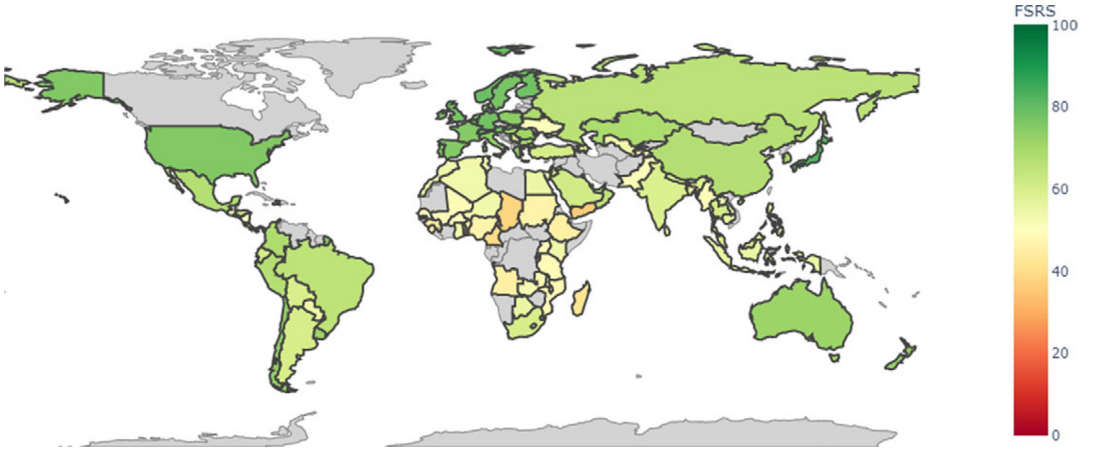

Figure 3. *A global map of FSRS obtained for 109 countries with 44 indicators. The countries in the American and European regions, including Australia and New Zealand in Oceania, have more resilient food systems than others.*

countries may lead to different sets of aggregation, leading to different composite scores. Additionally, different combinations of indicators may give inconsistent composite scores. The optimal coverage for FSRS was determined based on three criteria: the number of countries covered, the variability in FSRS, and the changes in the ranks of countries. The second and third criteria for the optimization of country coverage ensured the stability of the calculated scores. Figure 4 shows the FSRSs for four different countries from four income groups for different subsets of indicators. The FSRSs of four countries have stayed fairly stable, with a maximum change of 1.8 (Australia: 1.1, Colombia: 1.1, DR Congo: 1.8, and India: 1.2) in each step for a minimum of 10 indicators. The maximum average change in FSRSs for each step during optimization was 0.67 for the same. Similarly, the maximum average change in the ranks for the countries was about 3 places for at least 20 indicators, while the minimum average change was 0.44 for the subset of 44 indicators. These changes in the ranks are low, given the chance of new countries getting

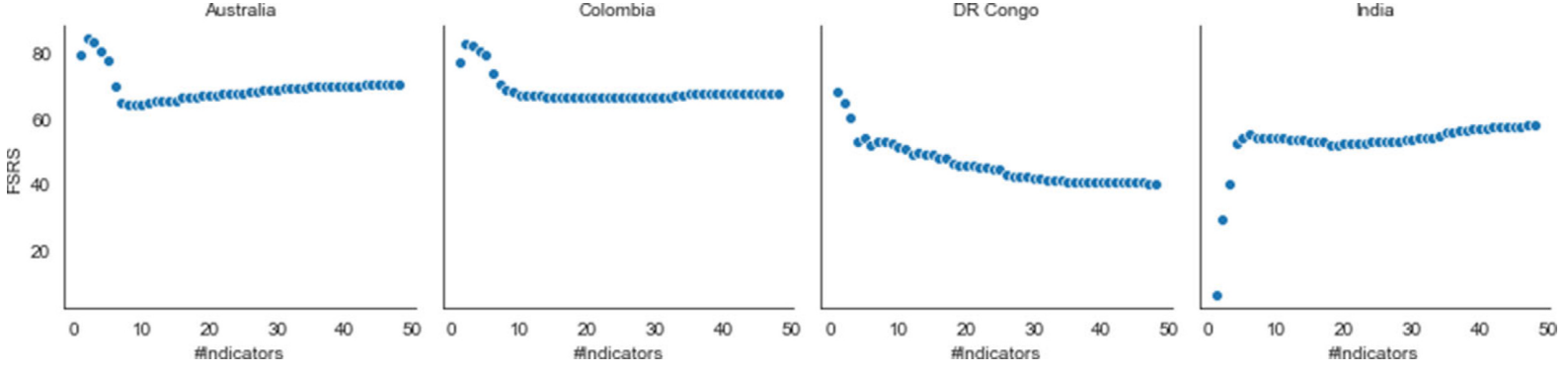

Figure 4. *Stability check. The FSRSs of four countries changed by a maximum of 1.8 in each step during the optimization of country coverage. The low value of the maximum change indicates the stability of FSRS.*

added in each step. The optimal combination of 109 countries and 44 indicators had an average change in FSRS of 0.04 and an average change in ranks of countries of 0.44 when compared to the subset of 43 indicators. These low values of the changes validate the stability of the final FSRS system.

3.3. Sensitivity analysis

With the unequal number of indicators included in various capitals within the composite score system, there is an issue of sensitivity to changes in different capital scores. The composite score may be more sensitive to the changes that occur in the capitals with fewer indicators (financial and natural) than to those in the capitals with more indicators (human and manufactured). Similarly, in terms of qualities, FSRS may be more sensitive to redundancy and rapidity than to robustness and resourcefulness, due to the number of indicators in each quality. Such sensitivity issues have existed in several other composite indexes, such as UNDP HDI and Multidimensional Poverty Index developed at OPHI-Oxford (Alkire et al., 2011), but have not prevented the use of such indexes in decision-making. The most important thing about such composite indexes is to quantify and understand the sensitivity of the composite score to the capitals before applying it to any decisions.

We randomly selected the indicators within capitals and qualities of FSR and changed them by 10–30% under two different scenarios of 10 and 20 randomly selected countries until we achieved the optimal combination of countries and indicators. Table 2 shows the percentage changes in the values of capitals and qualities, including FSRS, when indicators in each capital and quality are subject to changes. The highest change in FSRS is caused by the change in human capital and redundancy. Similarly, FSRS is least sensitive to changes in the manufactured capital and resourcefulness. The maximum change in FSRS during the sensitivity test was at −0.671% (human capital for 30% change) and −0.805% (redundancy for 30% change). We found the FSRS was not subject to the usual issue of sensitivity, where the composite scores are usually more sensitive to changes in capitals or qualities with fewer indicators. Additionally, the maximum of <1% change for up to 30% change in the indicator of the capital and quality indicates the robustness of FSRS, despite the unequal numbers of indicators in various capitals and qualities.

3.4. Comparison against GFSI ranking

One of the key steps for technical validation is to compare the performance of a new composite score system against one of the closest existing index systems. We compared the ranks of countries obtained with our FSRS framework against the GFSI ranks. GFSI, developed by Economist Impact and supported by Corteva Agriscience, captures the annual changes in structural factors impacting food security, which is one of the desirable outcomes of FSR.

Figure 5 shows the comparison between ranks for 108 countries (the Dominican Republic is not included in GFSI). More than half of the countries had a maximum deviation of five places, showing a close correlation between food security and FSR. However, some countries, such as Bulgaria (BGR-19) and Zambia (ZMB-19), had significant differences in their ranks estimated by our FSRS framework. This is not a surprise, as GFSI does not consider equal weights for all indicators as the FSRS framework does. Having relatively poor performance in a few indicators that are highly weighted in GFSI would degrade the country's rank, while the same may not be true with the FSRS framework. One of the key observations is that Singapore has an FSRS rank of 41 while its GFSI rank is 24. Singapore has a relatively high score for robustness, which is consistent with the high overall GFSI score. However, Singapore's scores for resourcefulness and rapidity are relatively low (59.3 and 50, respectively). The scarcity of natural resources, biodiversity, irrigation infrastructure, and community organizations collectively contributes to this lower rank and makes Singapore vulnerable to the impacts of chronic food shocks.

Table 2. *Sensitivity test*

10 countries									
Rate of change	Natural	Human	Social	Financial	Manufactured	Robustness	Redundancy	Resourcefulness	Rapidity
10%	−0.175	−0.240	−0.171	−0.277	−0.108	−0.223	−0.261	−0.094	−0.085
20%	−0.351	−0.480	−0.326	−0.450	−0.215	−0.432	−0.523	−0.187	−0.165
30%	−0.526	−0.647	−0.474	−0.550	−0.323	−0.578	−0.782	−0.187	−0.212
20 countries									
10%	−0.154	−0.240	−0.161	−0.254	−0.133	−0.239	−0.290	−0.099	−0.088
20%	−0.307	−0.470	−0.303	−0.403	−0.253	−0.415	−0.569	−0.198	−0.164
30%	−0.461	−0.671	−0.436	−0.515	−0.354	−0.532	−0.805	−0.297	−0.240

Note. FSRS is most sensitive to the change in the indicators of human capital and redundancy, while least sensitive to the change in the manufactured capital and resourcefulness. The low value of the maximum change in FSRS during the sensitivity test demonstrates the robustness of FSRS.

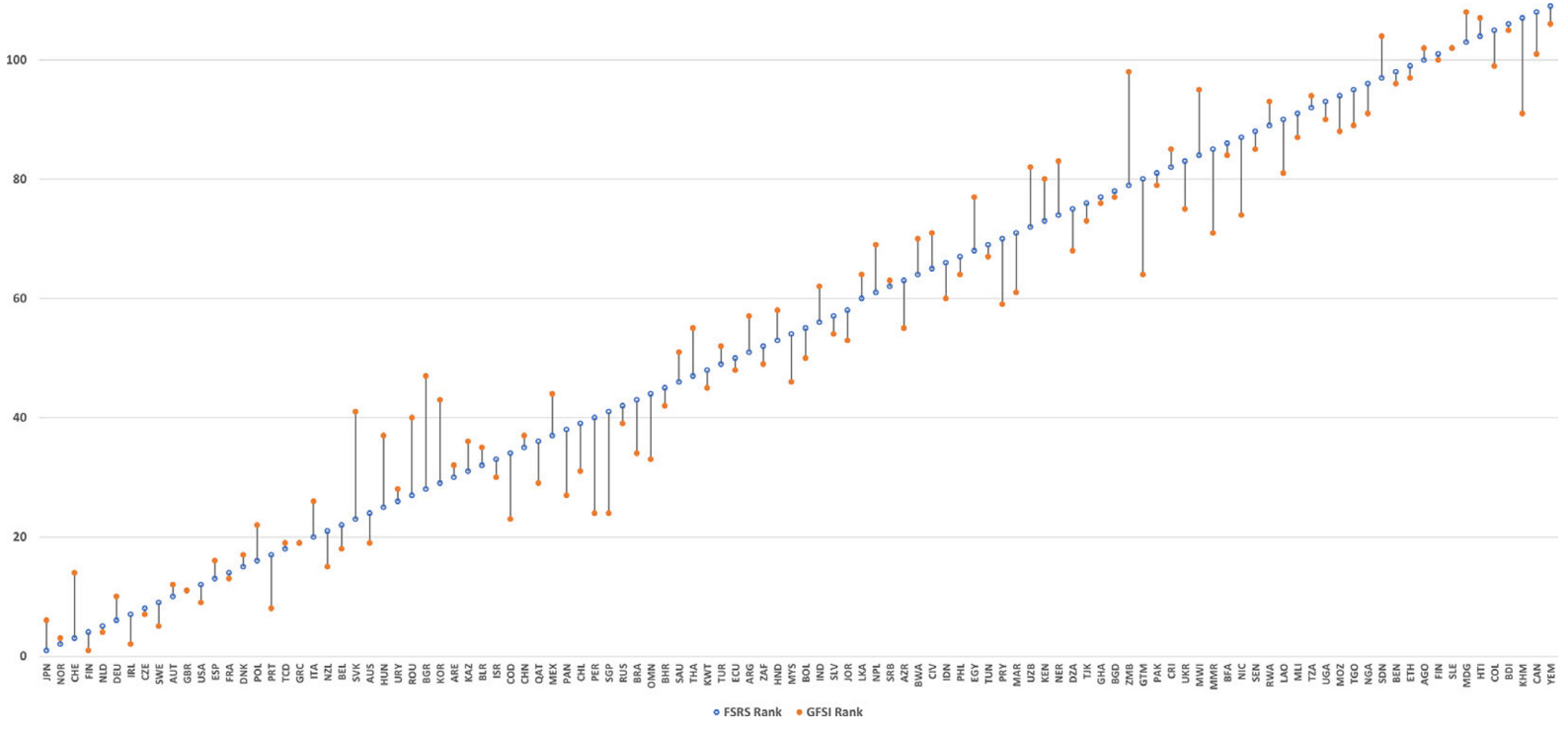

Figure 5. *FSRS rank comparison against GFSI rank.*

A contrasting example is Switzerland, which is highly ranked by our FSRS when compared with GFSI (FSRS rank 3 vs. GFSI rank 14). This is due to the country's high scores for all capitals and qualities. The focus of GFSI is centered around current food security, and the aggregation of the scores of indicators is done differently, thereby possibly giving less weight to highly performing indicators. Also, such a difference may point to the fundamental difference in the concepts of food security and FSR, as the ultimate goal of resilient food systems is food security (Berry et al., 2015).

4. Discussions and conclusions

4.1. Summary of key findings

Our FSRS framework optimally covers 109 countries with 44 different indicators, quantifying the resilience of food systems in five capitals (natural, human, social, financial, and manufactured) and four qualities (4Rs). The resultant composite scores obtained indicate significant variations in the resilience of food systems across countries, with Japan, Norway, Switzerland, Finland, and the Netherlands being the world's most resilient food systems.

The framework for FSRS is rooted in a systematic, transparent, rigorous, and reproducible methodology. We identified variables relevant to resilience thinking in food systems through a comprehensive review of the literature, which was then complemented by expert consultation. The use of existing indicators circumvents the need for resource-intensive data collection (Hatløy et al., 1998), while using publicly available datasets from development agencies and existing composite score systems makes it more transparent and accessible.

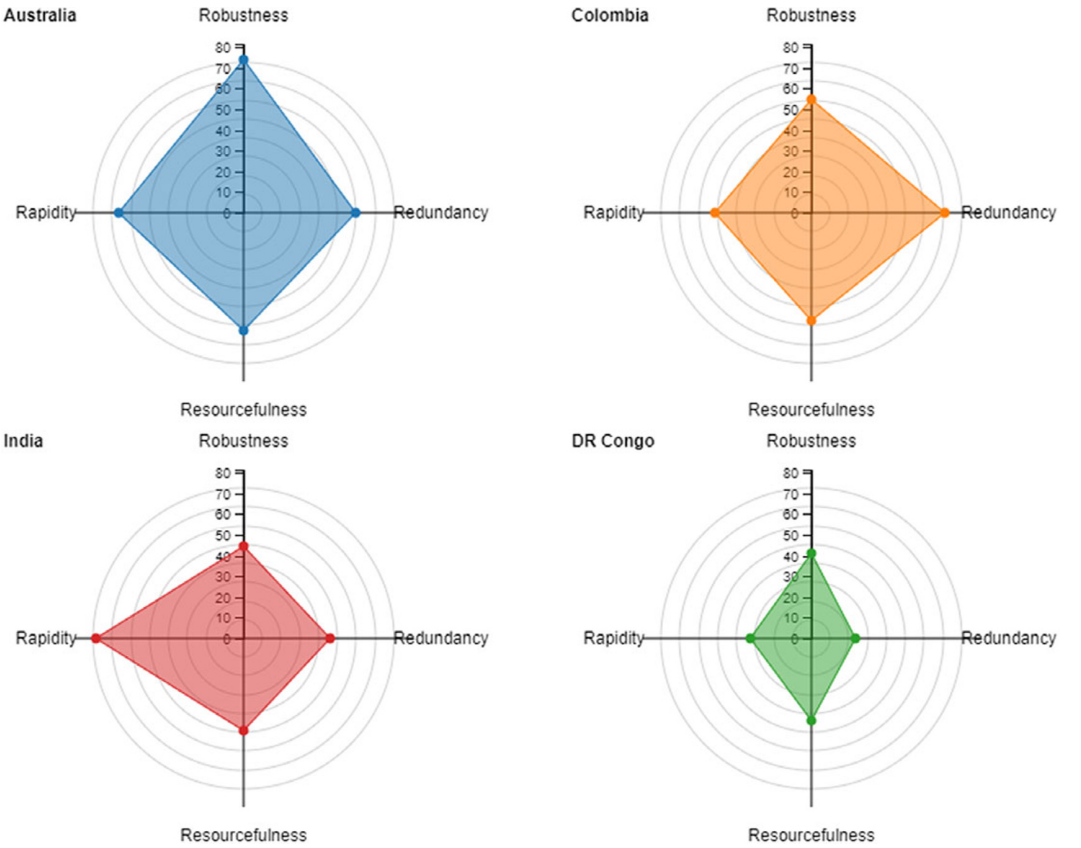

Figure 6. *Anticipating the performance of food systems when exposed to food shocks by operationalizing resilience as a combination of qualities. The Australian food system has the highest ability to withstand the impacts of shocks, while the Indian food system has the highest ability to bounce back after exposure to shock.*

The adaptation of the five capitals model of sustainability (DfID, UK, 1999) gives a holistic view of the food system's capacities and helps achieve the desired outcome by maximizing the value of each capital. Additionally, framing FSR as a combination of four qualities (4Rs) helps policymakers anticipate the performance of food systems when exposed to uncertain risks and opportunities. This approach not only measures the resilience of food systems but also anticipates how the systems may respond when exposed to food shocks.

Figure 6 depicts the FSR of four countries as a combination of four qualities, showing how different national food systems respond when exposed to food shocks. For instance, the Australian food system is more likely to withstand the impacts of a food shock at almost twice the rate of the food system in DR Congo. This visualization demonstrates the framework's ability to provide nuanced insights into the resilience profiles of different countries.

4.2. Policy implications

The FSRS framework serves as a powerful tool for policymakers, offering several key insights:

1. Targeted interventions: Figure 8 shows the scores of four countries for five capitals over time, revealing areas of declining performance. For example, recent years show declines in Australia (manufactured capital), Colombia (human, social, and manufactured), DR Congo (human and social), and India (human, social, and manufactured). These observations can advise policymakers on how to prioritize interventions to improve specific sectors and strengthen more resilient food systems. The temporality of the data allows for the potential identification of trends and potential areas of concern before they become critical issues.
2. Comparative analysis: The framework facilitates cross-country comparisons, allowing policymakers to benchmark the performance of their country with others and learn from more resilient systems. For instance, understanding why Japan and Norway ranked top can provide other countries with lessons to learn. This comparative aspect of the FSRS can facilitate better knowledge sharing and best practice transfer between national contexts.
3. Temporal tracking: The ability to track and monitor changes over time, as demonstrated in Figure 7, enables policymakers to measure the impact of their interventions and adjust policies accordingly. This is particularly useful in assessing the effectiveness of policies with a focus on improving FSR. For example, the figure shows degrading trends in recent years for Australia (redundancy and rapidity), Colombia (robustness, resourcefulness, and rapidity), DR Congo (redundancy and resourcefulness), and India (robustness and rapidity). Such insights can prompt timely policy changes.
4. Holistic approach: As it looks at more than one capital and quality, the FSRS encourages policymakers to adopt a holistic approach toward the resilience of food systems instead of working on isolated areas. This holistic approach makes sure that improvements in one area do not come at the expense of another, thus promoting balanced and sustainable development of food systems.
5. Crisis preparedness: Awareness of the strengths and weaknesses of a nation in various capitals and qualities can guide preparedness efforts for impending food shocks or crises. For instance, the Indian food system has the ability to quickly recover even if it lacks the resilience to buffer against the effects of food shocks over a long period. Such insights can guide the creation of focused strategies to improve overall system resilience.

4.3. Limitations

Our study, while providing a comprehensive framework for assessing the resilience of food systems, has several limitations that warrant discussion. First, our approach to selecting indicators, although systematic, may have excluded some relevant indicators on the basis of data availability or coverage. This could lead to overlooking some latent processes or nuanced aspects of resilience. For instance, indicators related to land access and ownership, crucial for measuring gender dynamics in agriculture, were not included

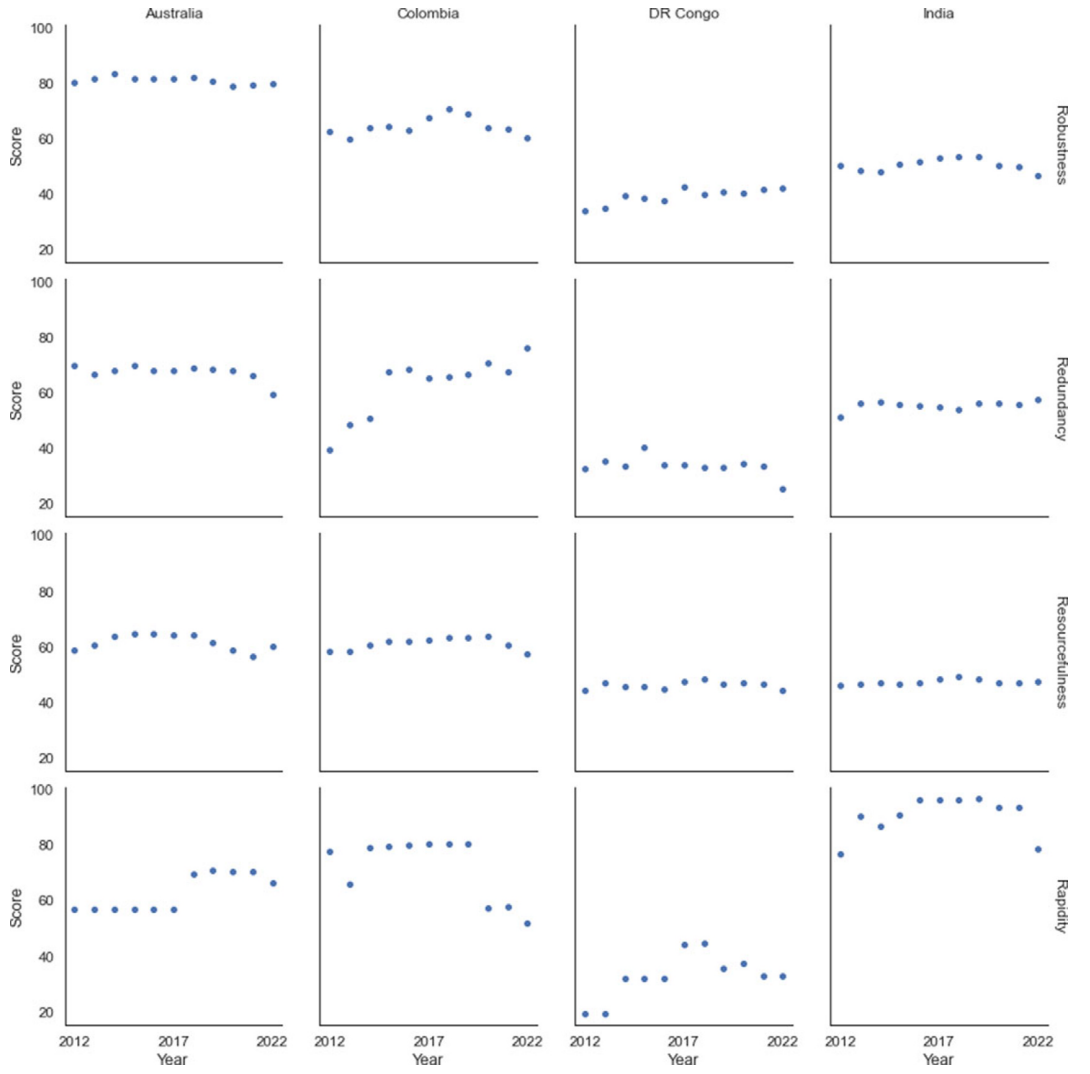

Figure 7. *Change over time in a country's scores for four qualities of resilience. Degrading trends in recent years: Australia (redundancy and rapidity), Colombia (robustness, resourcefulness, and rapidity), DR Congo (redundancy and resourcefulness), and India (robustness and rapidity).*

due to a lack of globally comparable data. Similarly, indicators of social capital at the community level, such as the strength of farmer cooperatives or local food networks, could not be included since there was no global standardized measure. These omissions may limit our framework's ability to capture some important facets of resilience, particularly those operating at more localized levels.

Second, the timeliness of available data poses a significant limitation. Our framework relies on data from international institutions that are often not updated frequently. For example, some indicators from the FAO or the World Bank only get revised after a few years. This lag in data update means that our FSRS may not be able to keep pace with rapid changes in resilience, particularly in the event of unexpected disasters or shocks. As a result, the FSRS would be unsuitable for estimating instantaneous pre- and post-disaster resilience. For instance, with a major drought or an unforeseen political crisis affecting the food supply chains, our framework might not reflect these shifts until the subsequent data update cycle, which may be several months or even years in the future.

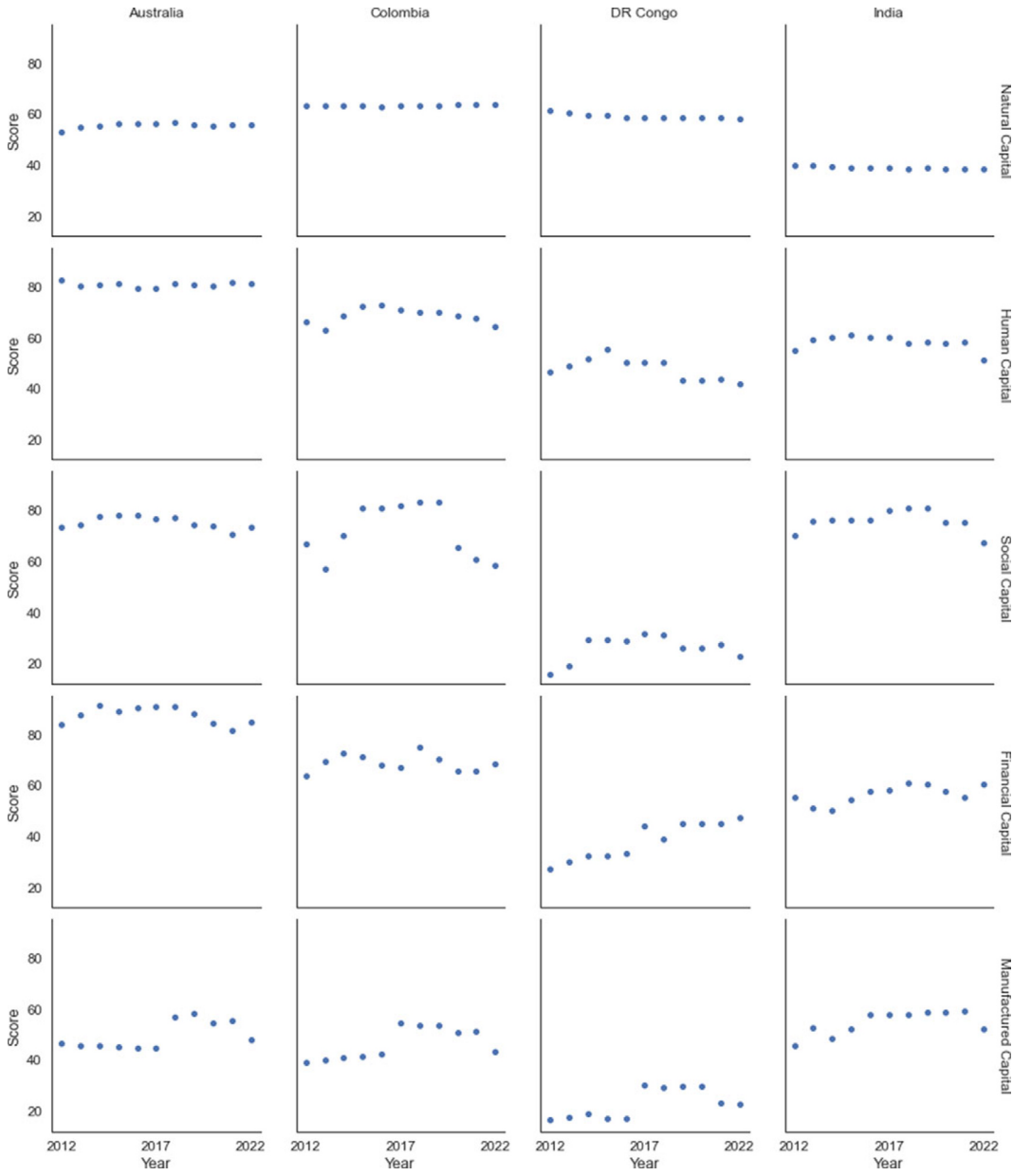

Figure 8. *Change over time in a country's scores for the five capitals of resilience. Degrading trends in recent years: Australia (manufactured), Colombia (human, social, and manufactured), DR Congo (human and social), and India (human, social, and manufactured).*

To address this limitation, we recommend complementing our framework with more frequently updated local measures at broader spatial resolutions when assessing resilience in rapidly evolving contexts. This can involve combining real-time data from national statistical offices, local extension services for agriculture, or even citizen science efforts monitoring food prices or crop health. For example, in determining the effect of an invasion by locusts on the resilience of the food system in East Africa, it is possible to merge our FSRS with current data on crop damage, food price fluctuations, and

emergency interventions to obtain a more precise estimation of the immediate resilience of the food system.

Despite these limitations, we believe the conceptual operationalization and methodological rigor of our work provide a solid foundation that can be reproduced or adapted for finer-scale assessments. The structure of the framework, as built using the five capitals and four qualities, can be maintained while substituting global indicators with more localized and frequently updated data sources. For instance, a community-level adaptation might replace our national-level agricultural production diversity indicator with data on local crop varieties cultivated, sourced from community agricultural offices. Similarly, the socioeconomic access indicator could be refined using local household survey data on food expenditure patterns. This flexibility allows for the framework to be tailored to specific contexts while maintaining its conceptual integrity and methodological robustness.

4.4. Conclusions and future directions

The FSRS framework discussed in this article offers a comprehensive and robust approach to quantifying the resilience of national food systems. The FSRS enables policymakers to make evidence-based, decision-making interventions by not only quantifying the current state of FSR but also projecting how systems will respond to future shocks and stresses.

Our composite score system can be customized to address the specific interests of geographical scenarios while considering the data availability (Achicanoy et al., 2019). For example, the FSRS in the European region may be able to use all the indicators in the full list, as the region is data-rich and may have data coverage for all countries for all indicators. Conversely, the scope of FSRS indicators may have to be reduced for the Pacific Region, where data are sparsely available. This flexibility enhances the framework's applicability across diverse contexts.

While the FSRS is a significant step forward in assessing FSR, there are areas for future research and development:

1. Establishing thresholds: Future work could focus on determining specific thresholds or benchmarks for resilience, providing clearer targets for policymakers. While our framework quantifies resilience, there is currently no direct threshold above which a country can be considered to have a resilient food system. Developing such thresholds could further enhance the framework's utility for policymaking.
2. Dynamic updates: Given the evolving nature of food systems, continuous updating of data and potentially the indicators themselves will be crucial to maintain the relevance of the FSRS. This could involve incorporating new indicators as they become available or as new aspects of FSR are identified.
3. Regional customization: Further research could explore how the FSRS can be customized for different regions, considering varying data availability and specific regional challenges. This could lead to more targeted and context-specific resilience assessments.
4. Integration with other frameworks: Investigating how the FSRS can be integrated with other sustainable development frameworks could enhance its utility in broader policy contexts. This could involve exploring links with frameworks related to climate change adaptation, disaster risk reduction, or sustainable agriculture.

A working prototype of a diagnostic tool based on this FSRS framework is available at https://rifa-diagnostics-tool.streamlit.app/. This decision-support tool provides policymakers the ability to understand, interpret, evaluate, and monitor key aspects of the food system and facilitate better decision-making to build and maintain resilient food systems in the long term. It is important to note that this is a decision-support tool rather than a decision-making tool, emphasizing its role in informing rather than dictating policy choices.

Overall, the FSRS framework is a significant breakthrough in our ability to quantify and build FSR. Through providing a nuanced, integrated, and flexible approach to measuring resilience, it has the potential to guide policymakers in formulating appropriately directed strategies for building and maintaining resilient food systems over the long term. This, in turn, has the potential to make a significant contribution to the United Nations' Sustainable Development Goal of Zero Hunger in 2030 and other sustainable development and global food security targets.

Data availability statement. The data supporting the findings of this study are openly available in KC et al. (2025).

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Competing interests. The authors declare none.

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