Food and Agriculture Organization of the United Nations

Resilient food systems

A proposed analytical strategy for empirical applications

Background paper for
The State of Food and Agriculture 2021

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Abstract

The food systems concept has attracted a considerable amount of attention as it provides an opportunity to better understand and represent the array of factors that explain food security in a comprehensive and holistic manner. The value-added proposition of food systems resilience is that the ability to respond to shocks and stressors may be incorporated into such explanations. The qualities that make food system resilience attractive, however, also make it difficult to model in empirical terms. This paper, by drawing on the literatures of food systems and on the measurement of resilience, demonstrates how food systems resilience can be measured at a country level. Clustering countries into regions shows that North America and Oceania have the highest levels of food systems resilience, followed by Europe and North Africa and Western Asia. Food systems resilience is lower in Latin America and the Caribbean and South Asia and sub-Saharan countries exhibited the lowest levels of food systems resilience. In low- and middle-income countries, increasing market resilience plays an important role in increasing overall food systems resilience.

Keywords: food system, resilience.

JEL codes: O12, N47, Q18.

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1 Introduction

This paper articulates and applies a model that can support efforts to empirically investigate how food system resilience has changed over time, across globe.[1] Over the past few years, recognition of two realities has brought the food systems concept to the centre of policy discussions for development (Willet *et al*., 2019; FAO, IFAD, UNICEF, WFP and WHO 2020; Webb *et al*., 2020; Barrett *et al*., 2021; Hertel *et al.,* 2021; Herrero *et al*., 2021). First, there is now wide and growing acceptance that an array of interacting factors underpins stable food and nutrition security. A reliance on models and policies that place too heavy an emphasis on production or on single component of a food system is insufficient (Reardon and Timmer, 2012; AGRA, 2020). Second and following naturally from the acceptance of the first reality, the efforts to achieve stable food and nutrition and security requires a more holistic perspective. The food systems perspective that acknowledges interactions and interdependencies that exist among the elements of that contribute to food and nutrition security. The High Level Panel of Experts on Food Security and Nutrition (HLPE) defined food systems as "… all the elements (environment, people, inputs, processes, infrastructures, institutions, etc.) and activities that relate to the production, processing, distribution, preparation and consumption of food, and the output of these activities, including socio-economic and environmental outcomes" (HLPE, 2017; FAO, 2018). This definition has been somehow endorsed and supported by the Food Systems pre-summit held in Rome during 2021 (UN, 2021). By including such a wide range of elements and activities in its definition, the food systems concept represents an opportunity to advance a more integrated strategic response to the challenges of food and nutrition security. How to translate this opportunity into and empirically testable problem presents an analytical challenge, one to which the present paper offers a response.

Recognizing the potential for a more integrated strategy, the international community has embraced the food systems concept. United Nations agencies, the international donor community, and the academic community have shown increased levels of activity centred on food security. As an illustration of the increased activity, a recent review of reports focused on food systems concepts by Brouwer *et al*. (2020) identified 32 high level reports issued over the past three years. The European Union (EU) has articulated a food systems strategy as a core feature – beginning in 2020 (EU, 2020). Frequent references are made to food systems in the 2016–2025 Food Assistance Strategy offered by United States Agency for International Development (USAID, 2020). The announcement of the 2021 United Nations Food Systems Pre-summit by the United Nations Secretary-General António Guterres in 2019 provides further evidence that the international community views food systems as a vital part of development strategy for achieving food security.

In parallel with the rise of the food systems concept, resilience has also gained momentum as a concept on which policies and programmes for food security may be based. In this analysis, we understand resilience as "…the capacity that ensures adverse shocks and stressors do not have long-lasting adverse development consequences" (Constas *et al*., 2014a).[2] Interest in resilience is grounded in an understanding that shocks and stressors affecting food and nutrition security have become are more severe and often less predictable. Climate change, degraded

[1] The concept of agri-food food systems, which includes food security and non-food agricultural outputs, is a concept that appears to be gaining traction in some of the writing about food systems (e.g., FAO *et al.,* 2021). The present paper uses a narrower term of food system, because the analysis uses food security indicators of undernourishment and food consumption as outcomes of interest.

[2] The majority of definitions in circulation similarly emphasize resilience capacities and their connection to development consequences (see Béné, 2020).

agro-ecological conditions, unstable governments, poorly functioning institutions, and the widespread and deep effects associated with COVID-19 (Devereux *et al*., 2020) draw attention to the need to incorporate resilience into food security policies, programming, and analyses.

Much of the work on resilience as applied to food and nutrition security has focused on households. This is true of both the early work on resilience (Pingali *et al.*, 2005; Alinovi *et al*., 2008, 2010) and more recent work (Barrett *et al*., 2021; Fan *et al*., 2021; Cissé and Barrett, 2018; d'Errico and Pietrelli, 2018; Knippenberg and Hoddinott, 2017; Knippenberg *et al*., 2019; Smith and Frankenberger, 2018). While a commitment to protecting and improving the lives of beneficiaries justifies household level analysis, the fact that shocks and stressors affect larger aggregates and disturb higher-level functions compels one to explore dynamics related to food systems resilience. Exploring points of intersection between food systems and resilience has theoretical and practical benefits. From a theoretical perspective, the integration of food systems and resilience has the potential to improve our ability to identify the conditions that explain variations in food and nutrition security. The need for empirically testable models of food systems is a point made in several articles (see for instance Barrett *et al.,* 2018; Lu and Reardon 2018), among which a review article on food systems by Reardon and Timmer (2012). From a practical perspective, viewing food systems through the lens of resilience draws attention to the various shocks and stressors that may threaten the functional integrity of food systems. When refined, the ability to estimate such threats may provide an improved, more temporally sensitive early warning system based in an understanding of food systems resilience. The availability of such evidence could sharpen the ability to make decisions on when and where interventions are most needed.

We note that that the idea of food systems resilience is not new. Early work on food systems resilience can be found in Pingali *et al*. (2005) where strategic responses to crises were explored at a conceptual level. Other more recent contributions include Tendall *et al*. (2015) and Schipanski *et al*. (2016). While the body of work on food system resilience continues to expand, conceptualizations that would allow food systems resilience to be measured and assessed remains underdeveloped. With that noted, this paper outlines an analytical framework for food systems resilience. This is accomplished by combining extant conceptual models of resilience measurement (Constas *et al*., 2014b) and theoretical formulations food systems (Savary *et al*., 2020; Zampieri *et al*., 2020) with guidance from a newly created data resource of food systems indicators (FSD, 2020). The combination of these three inputs (i.e., conceptual theoretical, and data resources) comprises the conceptual core of our proposed framework. To translate the conceptual model into an empirical problem, we adapt the Food and Agriculture Organization of the United Nations (FAO) Resilience Index Measurement and Analysis (RIMA) (see FAO, 2016).

Our paper is organized as follows. In part one, we provide brief summaries of how food systems and resilience have been defined and show how they may be integrated to inform food systems resilience analysis. We do this by offering a simplified conceptual model and basic data structure, the latter of which highlights points of intersection for specifying food systems resilience indicators. In part two, we describe the analytical approach for food systems resilience. Following basic measurement principles, our analytical model takes the conceptual framework for food systems resilience and uses it as a point of reference to specify a set of questions, followed by an empirical specification. In part three, we demonstrate how our proposed analytical approach of food systems resilience can be applied to an empirical problem at a country level. We conclude by outlining a research agenda intended to support the effort to further develop, test, and refine models of food systems resilience.

2 Food systems and resilience: Toward an integrated framework

As an integration of food systems and resilience, Tendall *et al*. (2015, p. 19) defined food system resilience as the "capacity over time of a food system and its units at multiple levels, to provide sufficient, appropriate and accessible food to all, in the face of various and even unforeseen disturbances". Food systems and resilience are both concepts that have been widely embraced in discussions about food and nutrition security. Each has its own place in offering an innovative way to conceptualize and address the challenges of food and nutrition security in development. In this section of the paper, we briefly summarize the value-added proposition of each of these two perspectives. With the aim of advancing a measurement approach, our overview of each perspective includes a discussion of associated measurement requirements. We conclude the section of the paper by offering an integrated perspective on food systems resilience.

Common portrayals of the food systems idea have several notable features. First, they are typically comprised of a sequence of components that begin with production and end with consumption. These components, which provide a reasonably comprehensive view of how food systems function help explain how food system failures lead to problems of food availability, food access, and food utilization aspects of food and nutrition security (the fact that the food stability component is a less prominent feature of food systems is a point we will return in our discussion of resilience). Second, models of food systems tend to include interactions and feedback loops that reflect a cyclical quality. Third, building on the HLPE (2017), Brouwer *et al*., 2020, noted that the "...food systems approach [makes] clear distinctions …between causes (drivers) and outcomes (effects) of food system transformation…".

A conceptual framework of food systems offered by HLPE highlighted how the traditional food security pillars of availability, access, and utilization (FAO, 2008) are supported by three main food systems component – **food supply chains**, **food environments** and **consumer behaviours** (HLPE, 2017). The **food supply chain** includes productions systems, storage and distribution, processing and packaging, retail, and markets. The **food environment** underlines the role of physical access to food (e.g., distance to markets), economics access (e.g., affordability), promotion (e.g., food messaging and advertising), and food quality and food safety. Lastly*, the* **consumer behaviour** component is focused on the choices people make in connection with the foods to which they have access. In this sense, it is most concerned with the utilization pillar of food security. Acknowledging the importance of context, the HLPE also describes drivers of food systems. Food systems drivers, which can influence one or more of the components of a food system, include biophysical and environmental drivers, innovation and technology drivers, political and economic factors, sociocultural drivers, and demographic drivers (HLPE, 2017).

The potential value of a food systems perspective is that it holds the promise of producing more complete explanations that account for the heterogeneity of observed food security and nutrition outcomes. From a measurement perspective, however, the food systems approach present itself as an unrealistic ambition; there are too many variables, too many contextual factors, too many interactions and feedback loops, and data are not readily available to model food systems. Data limitations will naturally influence what parts of a food systems may be feasibly incorporated into empirical analysis.

To proceed with a productive measurement plan, it is important to identify a strategy that will make the food systems measurement less unwieldy. Our basic strategy is to (1) leverage existing data sets that can provide ready access to food system indicators, and (2) rely on a conception of food systems that represents current thinking about how the food systems may be used. Following this strategy, our approach to measuring food systems begins with the Food Systems Dashboard (FSD, 2020; Fanzo *et al*., 2020). While not completely populated with variables needed to conduct a comprehensive empirical study of food systems, the Food Systems Dashboard (FSD) provides perhaps the most extensive selection of indicators available from a single source.

Resilience has long been a topic of interest among ecologists (Hollings, 1973), engineers (Hollsnagel, 2006) and psychologists (Richardson *et al*., 1990). Work in these other fields often focused on systems; for example, Hollings defined resilience as "…the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables" (Hollings 1973, p. 14). In the past decade, the amount of attention given to resilience by major international actors has increased significantly.[3] In contrast to other elements of the food system, there has been extensive attention paid to resilience at the level of households as consumers, often described as food security resilience or more generally as development resilience. Theoretical conception of resilience for development was first developed in Barrett and Constas (2014) and a variety of new approaches to resilience measurement has been proposed. Several of these are based on the concept of "resilience as an *ex ante* capacity" (an idea first discussed in ecology based (Folke *et al*., 2010); Walker 2006), others focus on the idea of "resilience as a normative condition."

As part of an emerging body of work that focused on the ability to maintain and/or recover well-being following shock exposure, a line of research that explores resilience capacities has been undertaken. Resilience as an *ex ante* capacity can be thought of as "the capacity to withstand or absorb sudden or chronic shock; cope with temporary disruption while minimizing the damages and costs from hazard; restore after an event; manage or maintain basic functions and structures to become suitable for future situation" (Birhanu *et al*., 2017, p.2). In the existing literature, this is operationalized in several ways.

One approach is that of "resilience as *ex ante* capacity". As a multidimensional concept, resilience capacity is understood in terms of absorptive, adaptive, and transformative capacities (Béné *et al*., 2012; Walker *et al*., 2004). Drawing on a framework offered by the Organization for Economic and Cooperation and Development (OECD, 2014) the World Bank describes the three components of resilience capacities (World Bank, 2018, p. 8).

- **Absorptive capacity:** The ability of people, assets, and systems to prepare for, mitigate, or prevent negative impacts of hazards to preserve and restore essential basic structures and functions, e.g., strengthening the walls of grain storage sheds, to enable them to withstand inclement weather, such as high winds and rain.
- **Adaptive capacity:** The ability of people, assets, and systems to adjust, modify or change characteristics and actions to moderate potential future impacts from hazards so as to function without major qualitative changes e.g., establishing an irrigation system for farmers previously dependent on rainfall to water their crops.

[3] National development agencies, such as the United States Agency for International Development (USAID) stated their commitment to resilience through policy statements (see USAID, 2012). In line with the Sustainable Development Goals (SDG), FAO, the World Food Programme (WFP) and the International Fund for Agriculture Development (IFAD) identified resilience as a strategic priority. The Strategic Objective 5 (SP5), shared by the United Nations Rome-based Agencies, directs resources and activities to "increase the resilience of livelihoods to threats and crises.

- **Transformative capacity:** The ability to create a fundamentally new system so as to avoid negative impacts from hazards e.g., shifting from agriculture to another means of income such as live-stock herding, given the chronic climate and disaster risk and stress the current system is facing.

Several investigators (e.g., Smith and Frankenberger, 2018; d'Errico and Pietrelli, 2018) have explored how absorptive capacities, adaptive capacities, and transformative capacities can help households and communities recover from various shocks. This work has demonstrated that all three capacities are important for some unit (e.g., individual, household, or community) to not suffer ".Long-lasting adverse development consequences" in the face of shocks and stressors. Related work but with a somewhat different lens and nomenclature is the Resilience Indicators for Measurement and Analysis (RIMA), developed by the Food and Agriculture Organization (FAO). An updated version, RIMA-II (FAO 2016), estimates four latent variables, labelled "pillars". One is assets (AST) and as such, is similar in spirit to the approaches based on the Sustainable Livelihoods framework. RIMA-II adds three additional pillars - Access to Basic Services (ABS), Social Safety Nets (SSN), and Adaptive Capacity (AC) – that are combined into an overall resilience capacity index (RCI).

A different approach, "resilience as a normative condition" is developed in Barrett and Constas (2014) and Cissé and Barrett (2018). Here, and also in Fan *et al*. (2014), resilience reflects the capacity to avoid adverse well-being states, rather than a capacity itself. Cissé and Barrett (2018) translate this conceptualization into an econometric method, estimating resilience as a conditional probability of satisfying some normative standard of living; for example, a food consumption score. Similar to other approaches, the household is the unit of analysis and the food systems perspective is not drawn upon as to model resilience.

Several reviews of resilience as applied to development have been carried out. While the reviews tend to emphasis the plurality of definitions (Patel *et al*., 2017), tools (Sharifi, 2016), and measurement frameworks (Shipper and Langston, 2015; Barrett *et al*., 2021) a good degree of convergence can be found. Across the various strands of work on resilience measurement, three fundamental data requirements are apparent.

- **Shocks and stressors.** The first data requirement is focused on the need to have indicators related to *shocks and stressors*. Data on shocks and stressors may include objective and subjective elements of risk exposure.

- **Resilience capacities.** The second data requirement draws attention to the need to identify indicators of resilience capacities that prevent some unit, such as household or community, from experiencing long- term negative effects from a shock.

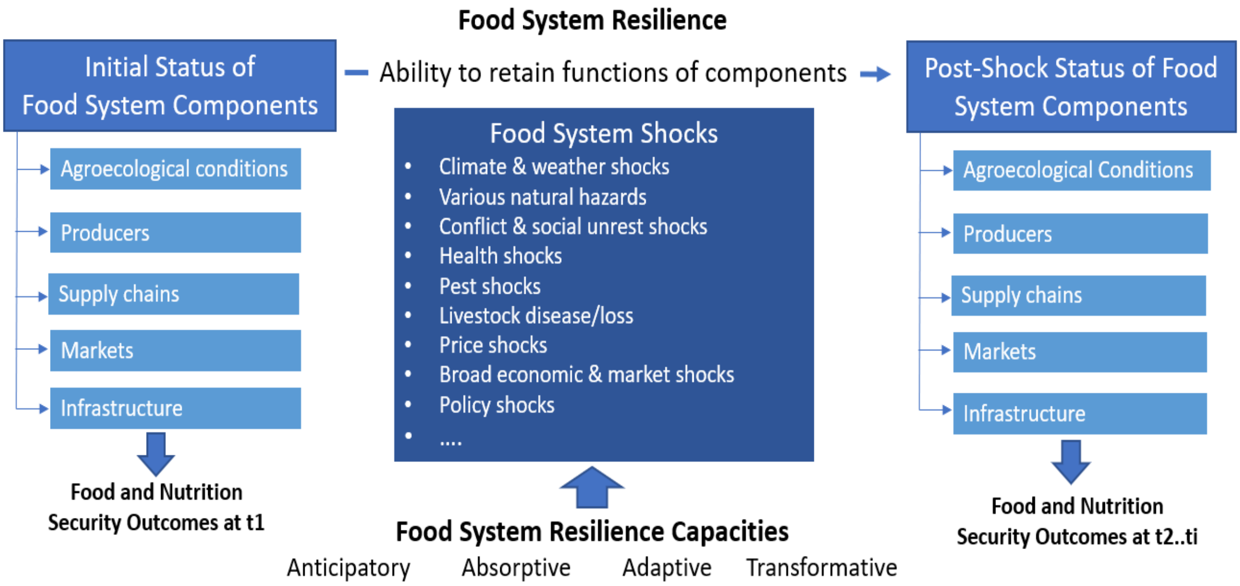
- **Well-being outcomes over time.** The third data requirement is focused on one or more well-being outcomes that can be tracked over appropriate time-period. The time dimension is important here because the state of bouncing back or bouncing back better should not be a temporary state. The other way in which time is important relates to the ability to remain above some critical threshold such a minimum food security level or minimum poverty level.

These three data requirements, which have been described as part of a common analytical model for resilience (Constas *et al*., 2014b) are regularly featured in resilience analysis. Each must be included in an analytical model of food systems resilience.

3 Integration of food systems and resilience: A conceptual model and a basic data structure

The conceptual integration of food systems and resilience draws attention to the need to understand what happens to one or more components of a food system when exposed to some shock(s) or the combined effects of some shocks. The difference between the status of food systems components at a pre-shock (t1) and post-shock (t2) intervals is an indicator of how well the components of given food system, and the food system as a whole, are able to cope with a shock. Food systems resilience capacities are comprised of the structural conditions, policies, strategies that a country, for example, may have in place as protections for component of a given food system. Here, as in other resilience work, food systems capacities may be viewed as providing anticipatory, absorptive, adaptive, or transformative capacities against shocks. The requirement of a well-being outcome as part of food system resilience underlines the importance of food and nutrition security outcomes at different points in time. A graphic portrayal of the set of relationships for which a food systems resilience analytical model will be developed is shown in Figure 1.

Figure 1. Food systems resilience conceptual model



Source: Constas (forthcoming).

We stress that the time dimension is crucial for the assessment of food systems resilience as well as the measurement of food and nutrition security outcomes. While measurement at two time points permit one to measure food system resilience, such measurement is rudimentary and potentially misleading. Similar to most outcomes measured in development where temporal features are crucial, resilience requires more than two time points. To determine if recovery is stable, observations beyond a short-term recovery are also important. Measurement of food systems resilience therefore requires t_1 to t_2 comparison and comparisons at additional time points (t_i).

Specifying a basic data-structure to organize indicators is crucial as we proceed in the direction of setting up an empirically testable analytical model. An integration of the key features of food systems and resilience specifies the basic data requirement for an analysis that is focused on food systems resilience. Following the food systems resilience conceptual model, the proposed data structure includes food system components agro-ecological conditions, producers, agricultural value chains markets, and infrastructure), and data on shocks and stressors that threaten the functional integrity of one or more components. To ensure that data will allow for resilience analysis as time-dependent process, indicators associated with shocks and resilience capacities are necessary. Consistent with the conceptual model presented in Figure 1, a comparison between ex ante and ex post status of food systems components is called for. Table 1 displays a simplified data structure for food systems resilience.

Table 1. Food systems resilience simplified data structure

Resilient food system simplified data structure				
Food system component	**Ex ante status**	**Shocks and stressors**	**Resilience capacities**	**Ex post status**
Agro-ecological conditions				
Producers				
Processors*				
Markets				
Infrastructure				
Measured outcomes: **Food system outcome:** Functional status of food system components and overall food system. **Well-being outcome:** Food and nutrition security at household level.				

Note: * Includes supply chains.

Source: Author's own elaboration.

Focusing on the food systems component, the need for multidimensional food systems metrics become apparent. Data to be included as part of the agro-ecological component might include, for example, indicators related to climate (rainfall and temperature), vegetation coverage, soil heath indicators, access to water for irrigation, and biodiversity. The data needed to capture resilience of producers, the processing sector and of food markets is somewhat more complicated. Examples for the infrastructure component might include indicators on roods and transportation, and food policies (e.g., food baskets, social welfare programmes).

4 Elements of the food system resilience analytical model

The food systems resilience analytical model proposed here is comprised of three elements – food production, food processing and markets. The way in which each of these elements contributes the proposed model is described below in brief.

4.1 Food production resilience

There are large literatures discussing development or food security resilience, the resilience of food systems, livelihood resilience, and the resilience of specific crops to biotic and abiotic stress (Valencia *et al*., 2019). However, there is much less explicit work on measurement of food production resilience, and more specifically on agricultural production. In part, this reflects enormous variations in how food is produced around the world. As well-described by Savary *et al*. (2020) "these production units include the large-scale commercial farms of the global North, with their high level of mechanization and inputs (synthetic and also biological, with highly selected and specialized seed) as well as the small-scale, smallholder farms of the global South, with their large labour force, their crop diversity, the frequent inclusion of livestock in agriculture, and their limited reliance on external inputs" (Savary *et al*., 2020, p. 695). That said, consider the notion of resilience as the capacity to withstand or absorb sudden or chronic shock. Measures of the resilience of food production can either be a summary statistic that captures this ability or as characteristics of the organization, structure and process of food production that are believed to be associated with the summary statistics. With the important caveat that the ideas below are exploratory, we describe both approaches below.

Before doing so, we briefly describe an analytical model valid for food production. The description here is best thought of one of a smallholder farming household producing annual crops in a developing country context. This household has endowments of capital and labour. The household allocates these endowments across a series of agricultural activities. (For simplicity, we ignore allocations to non-agricultural activities.) Once these allocations are made, shocks occur; these are outside the direct control of the household. They could be covariant or idiosyncratic and can be either negative or positive. The farming household may respond to these shocks through undertaking compensating or reinforcing actions (for example, undertaking additional weeding in fields affected by a weed-infestation, spending more time harvesting a field where production had been atypically high).

Different from typical representations of food production, a summary simple statistic of food production resilience captures the outcome of these allocations, the shocks and the compensating or reinforcing actions can be measured in physical or monetary terms; it does not attempt to disaggregate or disentangle how the outcome has come about. One such summary statistic is outlined in Zampieri *et al*. (2020); a simplified version of their approach goes as follows.

Consider circumstances where the shocks adversely affecting food production are so severe, or the ability of farming households to respond to shocks so limited, that the consequence of the shocks is total crop failure. The probability that this occurs is given by F where $0 < F < 1$. We can think of a farm (or locality or country) with resilient food production as the reciprocal of the probability of total crop failure.

$$R = 1/F \tag{1}$$

As F -> 0, R rises in value. As F -> 1, R approaches, 1 and so an increase in the value of R captures the notion of greater resilience of food production. Next, make the strong assumptions that mean production over time and variations in production over time are both trendless. Following Zampieri *et al*. (2020) define P as the level of production that occurs when conditions are optimal and allow only two states of the world: one where crop production is optimal and one where crop production fails totally. With these strong assumptions in mind, over time, the mean and variance of food production are given by:

$$\mu = P(1 - F) \quad (2)$$

and

$$\sigma 2 = P2\ (1-F)(F) \quad (3)$$

Zampieri *et al*. (2020) show that manipulating these expressions yields:

$$R = \mu 2 / \sigma 2 \quad (4)$$

Equation (4) is the summary statistic. Food production resilience is the inverse of the coefficient of variation of production squared. Note that this is consistent with intuition. Shocks that lead to total crop production failure are less likely when mean production levels are higher (the numerator). Food production that anticipates and copes with shocks and stressors is less variable (the denominator). Zampieri *et al*. (2020) show how to adapt this approach to circumstances where production is non-stationary or where more than one crop is produced.

4.2 Resilience in the food-processing sector

Globally, the food-processing sector is enormously heterogeneous, ranging from the large meat processing plants to women grinding grain harvested from their own fields. Unlike food security, there are no well-developed, validated metrics for resilience in the food-processing sector. Nor, unlike food production or food markets, are there measures that can be adapted to capture aspects of resilience. That said, literatures on supply chains and on recent experiences arising from the COVID-19 pandemic suggest several possible metrics that could be developed to capture resilience within the food-processing sector.

The supply chain literature (Aboah *et al*., 2019) argue that flexibility is a key attribute in the resilience of food value chains (see also, Linkov *et al*. [2020]). Applying their approach specifically to the processing sector, flexibility includes the ability to re-organize production/processing in response to a shock; obtain raw foods from other sources should shocks and disruptions affect existing suppliers; and tap alternative distribution channels. Relatedly, stock holdings can also play a role by reducing processors vulnerability to transitory shocks in the supply of inputs.

COVID-19 experiences: Taylor *et al*. (2020) document the spread of COVID-19 within United States livestock plants. They note that such operations are susceptible to the transmission of coronaviruses for several reasons, including that the employees work long shifts in close proximity to co-workers. They also note that in the United States of America, 12 plants produce more that 50 percent of the country’s beef and 12 other plants are responsible for more than 50 percent of pork production, which makes the case for labour force concentration. Rotz and Fraser (2015) also document increased concentration within the North American food processing sectors. Given all this, Savary *et al.* (2020)'s description of how COVID-19 affected the North American food-processing sector is not surprising. "Labour shortages have also been an issue for large-scale food processors and suppliers. A growing number of workers are taken ill in food processing facilities where the operational model is not conducive to safe physical distancing. Consequently, a large number of food processing plants temporarily suspended production in Europe and North America (Savary *et al*. 2020).

Putting these disparate studies together suggests that resilience within the processing sector reflects three considerations: (a) the extent of market concentration within the sector. Countries where food processing is dominated by a small number of firms may be less resilient to shocks that affect their workforces; (b) the availability of substitutes. While the shocks described by Savary *et al*. (2020) were disruptive – particularly for meat processing and packaging – the availability of other sources of animal source foods – lessened their impacts on consumers; and (c) more speculatively, the degree of labour intensity within the processing sector with greater intensity associated with lower resilience (Reardon and Swinnen, 2020).

4.3 Resilient food markets

There is a vast academic literature on the structure, conduct and performance of food markets in both developing and developed countries. This literature rarely speaks directly to the notion of resilient food markets. However, the literature on spatial market integration provides relevant insights.

We begin with an adaptation of the Takayama – Judge model described by Fackler and Goodwin (2001), Fackler and Tastan (2008) as a point-location model. Points or nodes represent geographically separated locations. Assume that there no node is connected to another. Within each node, the price of a food is determined by local production (supply) and local demand. An adverse shock occurs causing supply to fall. With no means of offsetting this, food prices rise and remain persistently high until supply is restored. In extreme versions of this (and where there are no offsetting increases in wages or income), the result is famine; see Devereux (1988) and Ravallion (1987, 1997). Seen in this way, these unconnected geographically separated food markets are not resilient – they lack the capacity to withstand or absorb sudden or chronic shock and their recovery – the extent to which prices return to their pre-shock state – is slow.

Next, we relax the strong assumption that no node is connected to another by introducing a set of transportation routes or links. Links and nodes together constitute a trade (market) network (Fackler and Tastan 2008). Again, consider a supply shock in one node. The initial effect is to raise prices in that node but, by so doing, prices differ across the two nodes. Traders can exploit this through arbitrage, buying food in the node not affected by the supply shock, then transporting it to and selling it in the node where the supply shock occurred. This has the effect of slowing the rise in food prices in the affected node allowing them to return to their pre-shock state more quickly. However, it also, potentially, causes prices to change in the non-affected node. The extent of the transmission of the exogenous price shock in the affected node to prices in the non-affected node is captured by measures and methods of assessing market integration. These include error correction models, cointegration analysis and parity bounds models (von Cramon-Taubadel, 2017; Kabbiri, *et al*., 2016; Varela, *et al*., 2012).

With caveats that we return to below, we assert that more integrated food markets are more resilient food markets. In turn, this takes us to the question as to what features influence the extent to which markets are integrated. This fall into four categories: (1) information flows; (2) transactions costs; (3) government regulations on trade; and (4) market structure.

Knowing that prices differ across markets is necessary for arbitrage to take place (Jensen, 2010). Measuring these information flows is challenging. A proxy measure used in a handful of studies is some measure of access to communications technology. An older study by Goletti *et al*. (1995) examining rice market integration in Bangladesh between 1989−1992 found that the number of telephones per capita was associated with reduced market integration, a somewhat counter-intuitive finding. By contrast, Aker (2010) finds that the introduction of mobile phones reduces dispersion in prices in rural Niger and Jensen (2007) shows how arbitrage in south Indian fish markets increased after the introduction of mobile telephony.

Transaction costs may also market integration. Ceteris paribus, these will be higher the farther markets are away from each other and several studies show this (for example, see Varela *et al*., 2012). Direct measures of transaction costs are rare, however with Zant (2013) being an exception and FAO (2015) another. Instead, road density and quality are used as proxies for transaction costs – higher quality roads can be travelled more quickly and can support larger vehicles, allowing for greater economies of scale in transport. Scale economies may also arise when markets are larger (put differently, per unit transportation costs are an inverse function of volume, Jensen, 2010). Some studies capture this idea of scale economies by including measures of the size of the market, population or population density or incomes per capita.

Government regulations on trade as well as the broader legal and policy environment in which trade takes place will affect arbitraging across spatially separated markets. The strongest version of these are prohibitions on the movement of food products across administrative borders. Requirements that marketed surpluses be sold to state-owned entities accompanied by the use of fixed, below market procurement prices are another form of intervention as is the use of government buffer stocks (both purchases for and sales to). Dercon (1994) and Rozelle *et al*. (1997) document that reductions in government involvement in grain markets in Ethiopia and China respectively improved market integration. That said, Ismet *et al*. (1998) argue that government intervention in Indonesian rice markets enhanced market integration but with the caveat that procurement prices were relatively high.

Market structure could contribute to either enhancing or detracting from market integration. As Kabbiri *et al*. (2016) note, market concentration may allow for economies of scale in the collection of information on prices and on transport, thus allowing such traders to respond more quickly to price differentials. However, they also note that traders may also have an incentive to keep markets segmented to keep prices artificially high.

We end with two inter-related caveats. First, the description provided here focuses on domestic markets. Integration into regional and/or global markets can also provide resilience to domestic food markets as well as potentially reducing prices. Just as with domestic food markets, the quality of infrastructure linking markets in different countries along with the regulatory environment – specifically rules and tariffs governing cross-border trade – will affect the extent of market integration; see Brenton *et al*. (2014) for an example. Second, that said, food markets that are more regionally and globally integrated are more likely to be affected by shocks that occur elsewhere, see Bekkers *et al*. (2017) for an example.

Measuring Country-Level Food Systems Resilience: A FAO-RIMA approach

Building on our conceptual approach, in this section we construct a measure of food systems resilience at the country level. Doing so is challenging for multiple reasons:

- Resilience is a latent construct, one not directly measurable.
- There is no one single measure for the latent constructs.
- As discussed below, data on important components of the food system are not available.
- Even where proxy indicators for these components are available, they are not available for all countries at all-time points.
- Food systems are comprised of multiple components. A country-level measure of food system resilience requires that these be aggregated.

Some of these challenges mirror challenges faced when estimating household-level food security resilience. With this in mind, we adapt FAO's Resilience Index Measurement Analysis (RIMA) approach to estimating country-level food systems resilience. The four pillars normally employed (and above mentioned in this paper – AST, ABS, AC and SSN) are now substituted by three components of food system resilience. The components are those mentioned above in this paper, namely production, processing and markets. RIMA is a data-reduction mechanism that allows to first estimate the different components of the food system, and then a Food System Resilience Index (FSRI) by anchoring the components to an outcome of interest, namely food security. We first assemble a country-level data set of proxy indicators of three components of the food system (production, processing and markets; see below for details on these proxy indicators) as well as indicators of the outcome of interest, (food security). We then build a model that specifies how the unobserved constructs are measured. Specifically, we apply a data reduction technique, factor analysis, to each of these constructs, including only those factors that explain at least 95 percent of the variables' variance. Finally, we estimate a structural model – the Multiple Indicator Multiple Causes (MIMIC) model – that specifies the relationships between these latent variables. Doing so allows us to calculate a FSRI.[4] More formally, we estimate the following: Equation (5), reflecting the fact that the observed indicators of food security (the prevalence of undernourishment and consumption per capita) are imperfect indicators of resilience index – and the structural equation (6), which correlates to the estimated components of food system resilience capacity, expressed as the FSRI:

$$\begin{bmatrix} Undernourishment \\ Consumption \end{bmatrix} = [\Lambda_1, \Lambda_2] \times [FSRI] + [\varepsilon_1, \varepsilon_2] \tag{5}$$

$$[FSRI] = [\beta_1, \beta_2, \beta_3] \times \begin{bmatrix} Production \\ Processing \\ Markets \end{bmatrix} + [\varepsilon_3] \tag{6}$$

Lastly, to ease interpretation, we re-scale the FSRI from 0 to 100 (where 0 is the minimum predicted value and 100 is the maximum predicted value) based on results from estimating the MIMIC model.

[4] The adoption of MIMIC to measure macroeconomic indicators is not new. Examples include Frey and Week-Hannemann (1984), Tedds (2005), Chaudhuri *et al*. (2006), Dell'Anno (2007), Farzanegan (2009), Schneider *et al*. (2010), Tafenau *et al*. (2010), Buehn and Farzanegan (2013) and Hassan and Schneider (2016).

4.4 Data and MIMIC model results

Table 2 describes the data we use for our analysis, along with their source and the years for which they are available. Our primary sources are FAOSTAT and the Johns Hopkins University Food Systems Dashboard (Fanzo *et al*., 2020; FSD, 2020).[5] Additional data are taken from the World Bank's World Development Indicators. We take three-year averages over the period 2015–17. The most recent year for which our production and processing indicators are available is 2017. Three-year averages allow us to smooth out the effects of random measurement error in these indicators. Means and standard deviations for these variables are found in Table A1 in the Annex. We have data for 136 countries. Excluded countries, and reasons for their exclusion are found in Table A2 in the Annex. The data we have cover 70 percent of the countries and 93 percent of the population of the world.

Table 2. Data sources

Food system component	Indicator	Definition	Source	Years
Production	Cereal yield sq. mean	Amount of harvested cereal production (Kg) per hectare of harvested land. Cereals include maize, millet, rice, sorghum, wheat, barley, oats, and rye, among other grains. Squared mean values calculated over three years' window.	Food Systems Dashboard (FSD) – FAO, FAOSTAT	1961–2017
	Cereal yield variance*	Variance of the harvested cereal production (Kg) per hectare of harvested land over three years' window.	FSD – FAO, FAOSTAT	1961–2017
	Vegetable yield sq. mean	Metric tons per hectare of vegetable yield. Squared mean values calculated over three years' window.	FSD – FAO, FAOSTAT	1961–2017
	Vegetable yield variance*	Variance of the harvested vegetable production (in metric tons) per hectare of harvested land over three years' window.	FSD – FAO, FAOSTAT	1961–2017
Processing	Cereal losses*	Cereal losses as percent of domestic supply: Quantities of cereal crops that are lost during storage, distribution, and processing, as a percent of domestic supply. This amount does not include quantities lost before or during harvest, and does not include quantities lost at the household as part of consumption (i.e. food waste). Cereals include maize, millet, rice, sorghum, wheat, barley, oats, and rye, among other grains.	FSD – FAO Food Balance Sheets (FBS)	1961–2017

[5] The Food System Dashboard was developed by Global Alliance for Improved Nutrition (GAIN) and Johns Hopkins University. This platform, which uses the HLPE framework as a blueprint for the dashboard, offers approximately 150 indicators grouped under four food system components - supply chains, food environments, individual factors, and consumer behaviours or consumption (Fanzo *et al*., 2020; FSD, 2020). While these components are not the same in name as those in the model we propose, the pool of associated indicators serve as good resource for our analysis.

Food system component	Indicator	Definition	Source	Years
	Pulses losses*	Fruit losses as percent of domestic supply: the decrease in quantity of fruit that occurs along the food supply chain from post-harvest up to, but not including, retail. This data does not include fruit losses that occur before or during harvest, nor food waste, which commonly refers to food that is lost during retail or at the household level.	FSD – FAO FBS	1961–2017
	Vegetable losses*	Vegetable losses as percent of the domestic supply: the decrease in quantity of vegetables that occurs along the food supply chain from post-harvest up to, but not including, retail. This data does not include vegetable losses that occur before or during harvest, nor food waste, which commonly refers to food that is lost during retail or at the household level.	FSD – FAO FBS	1961–2017
	Fruit losses*	Fruit losses as percent of the domestic supply: the decrease in quantity of fruit that occurs along the food supply chain from post-harvest up to, but not including, retail. This data does not include fruit losses that occur before or during harvest, nor food waste, which commonly refers to food that is lost during retail or at the household level.	FSD – FAO FBS	1961–2017
Markets	Mobile cellular subscriptions	Mobile cellular subscriptions (per 100 people): subscriptions to a public mobile telephone service that provide access to the PSTN using cellular technology. The indicator includes (and is split into) the number of post-paid subscriptions, and the number of active prepaid accounts (i.e. that have been used during the last three months). The indicator applies to all mobile cellular subscriptions that offer voice communications. It excludes subscriptions via data cards or USB modems, subscriptions to public mobile data services, private trunked mobile radio, tele point, radio paging and telemetry services.	World Bank indicators	1980–2019
	Road density	Meters of road per squared kilometre of land area. Roads may include highways, primary roads, secondary roads, tertiary roads, and local roads.	FSD – Meijer *et al.* (2018)	2018
	Percentage of urban population	Percent urban population of total population.	FSD – World Bank	1960–2019

Food system component	Indicator	Definition	Source	Years
Food security	Prevalence of undernourishment*	The prevalence of undernourishment expresses the probability that a randomly selected individual from the population consumes an amount of calories that is insufficient to cover her/his energy requirement for an active and healthy life. The indicator is computed by comparing a probability distribution of habitual daily dietary energy consumption with a threshold level called the minimum dietary energy requirement.	FSD – FAOSTAT Food Insecurity	2000–2017
	Consumption expenditure	Household final consumption expenditure is the market value of all goods and services, including durable products (such as cars, washing machines, and home computers), purchased by households. Data are converted to constant 2011 international dollars using purchasing power parity rates from the International Comparison Program (ICP).	FSD – World Bank, Global Consumption Database	1990–2018

Notes: * The indicators are included in the estimation of the Food System Resilience Index (FSRI) as inverted. All the indicators, with the exception of road density available only for 2018, have been centred on three-years mean, from 2017 back.

Source: Author's own elaboration.

We note the following features of these data. First, our empirical measure of food production resilience hews closely with the summary statistic, the inverse of the coefficient of variation of production squared. To capture a range of production activities, we calculate this for both cereals (wheat, maize, rice or also millet and others) and, as a proxy for non-cereals, also for vegetables (in future work, it would be possible to assess the robustness of this approach by including other crop types).

Second, we asserted that more integrated food markets are more resilient food markets. But while there is data on market integration for some crops in some countries, there is no systematic database of market integration studies for all countries and a reasonably numbered set of foods. We also noted that four features influenced the extent to which markets are integrated: (1) information flows; (2) transactions costs; (3) government regulations on trade; and (4) market structure. We do have data on mobile cellular telephone subscriptions, road density and the percentage of urban population. As explained above, these indicators are proxy for information flows (mobile subscriptions) and transactions costs (specifically road density) that increase market integration. Note that data on road density variable are only available for one year, 2018, and so we are unable to construct a three-year average. This limitation is offset by the fact that of all the variables we consider, it changes least over short periods of time. We do not have data on government regulations on trade or on market structure.

We have even less information on characteristics associated with resilience within the processing sector. As a very coarse proxy, we include losses during storage, distribution, and processing of four crop types (cereals, pulses, vegetables, fruit) as a percentage of domestic supply. Our logic is that more resilient processing sectors, ones that are better able to respond and adapt to shocks, will experience lower losses. For example, exposing food to high temperatures and/or moisture may increase bacterial growth that renders food unsafe to consume. Lower losses are indicative of storage and distribution practices that increase the resilience capacity of the processing sector.

For food security, we use the prevalence of undernourishment and consumption per capita. In the absence of cross-country data on diet quality (such as measures of diet diversity), the logic here is that the prevalence of undernourishment proxies for inadequate dietary quantity while – following Bennett's Law – the share of starchy staples in the diet falls with consumption per capita captures diet quality.

Results of estimating our MIMIC model are presented in Table 3. We note the following. First, given the severe limitations of our measures of resilience in the processing sector, we present results with (column 1) and without (column 2) the variables used to construct our resilience index for that sector. Second, as is well understood, there are a myriad number of statistical diagnostic tests for MIMIC models (as there are for structural equation models in general) and no consensus on which is the single best test to use and report. Mindful of that caveat, we note that our chi-squared tests do not reject the predicted model and the observed data are equal. Results from the Tucker-Lewis Index (TLI) and the Comparative Fit Index (CFI) tell us that we have good relative fit while the low values of the Root Mean Square Error of Approximation (RMSEA) tell us that measures of absolute fit are also good.

Table 3. MIMIC results

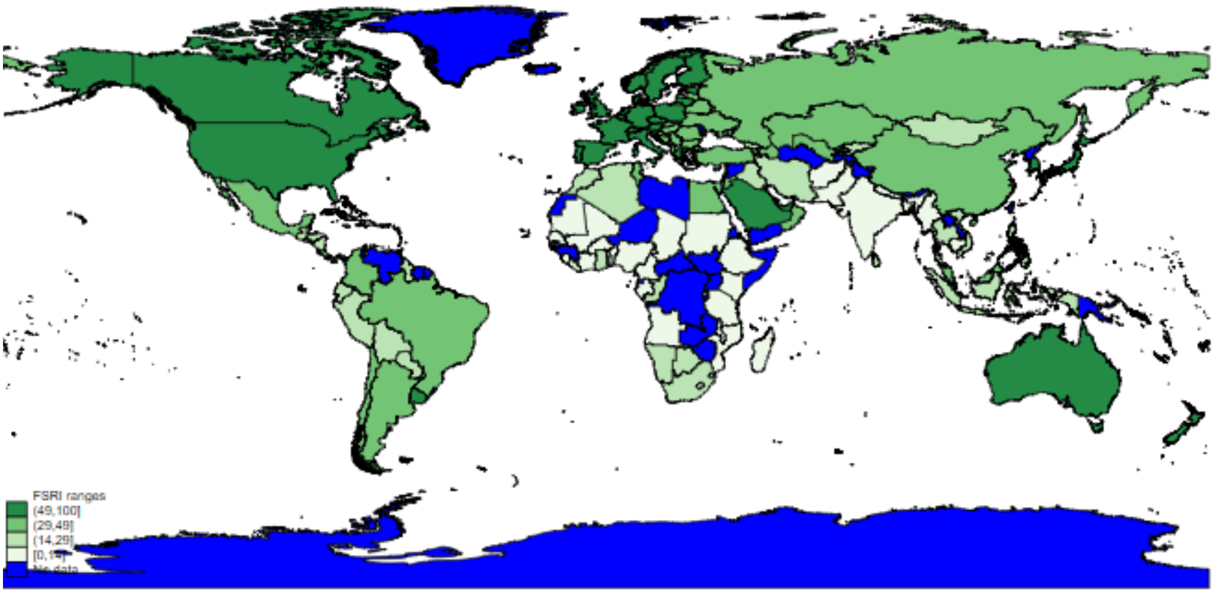
	(1) MIMIC model with 3 food system components	(2) Reduced MIMIC model with 2 food system components
Production	0.147***	0.144***
	(0.0195)	(0.0192)
Processing	0.0145	
	(0.0235)	
Markets	0.153***	0.159***
	(0.0215)	(0.0203)
Undernourishment (inv.)	1	1
	(0)	(0)
Consumption	0.535***	0.532***
	(0.0454)	(0.0451)
Observations	136	137
chi-2	5.74	1.11
TLI	0.948	0.998
CFI	0.985	1.000
RMSEA	0.118	0.029

Source: Author's own elaboration.

4.5 Results

Food System Resilience Indices for 136 countries are presented in Figure 2 with the underlying numerical values found in Table A3 in the Annex. These are based on the MIMIC model using all three (production, processing, markets) components. Figure 3 provides box-and-whiskers plots of the FSRI by region. Food systems resilience is highest in North America (Canada and the United States of America) and Oceania (primarily Australia and New Zealand). It is relatively high in Europe but with a few countries having relatively high and low resilience. Food systems resilience is lowest in sub-Saharan Africa with the other regions (North Africa and Western Asia, Latin America and the Caribbean and Central, Eastern and Southern Asia) falling somewhere in between. We also constructed these figures using only the production and distribution components. These are found in Figures A1 and A2 in the Annex and show similar patterns.

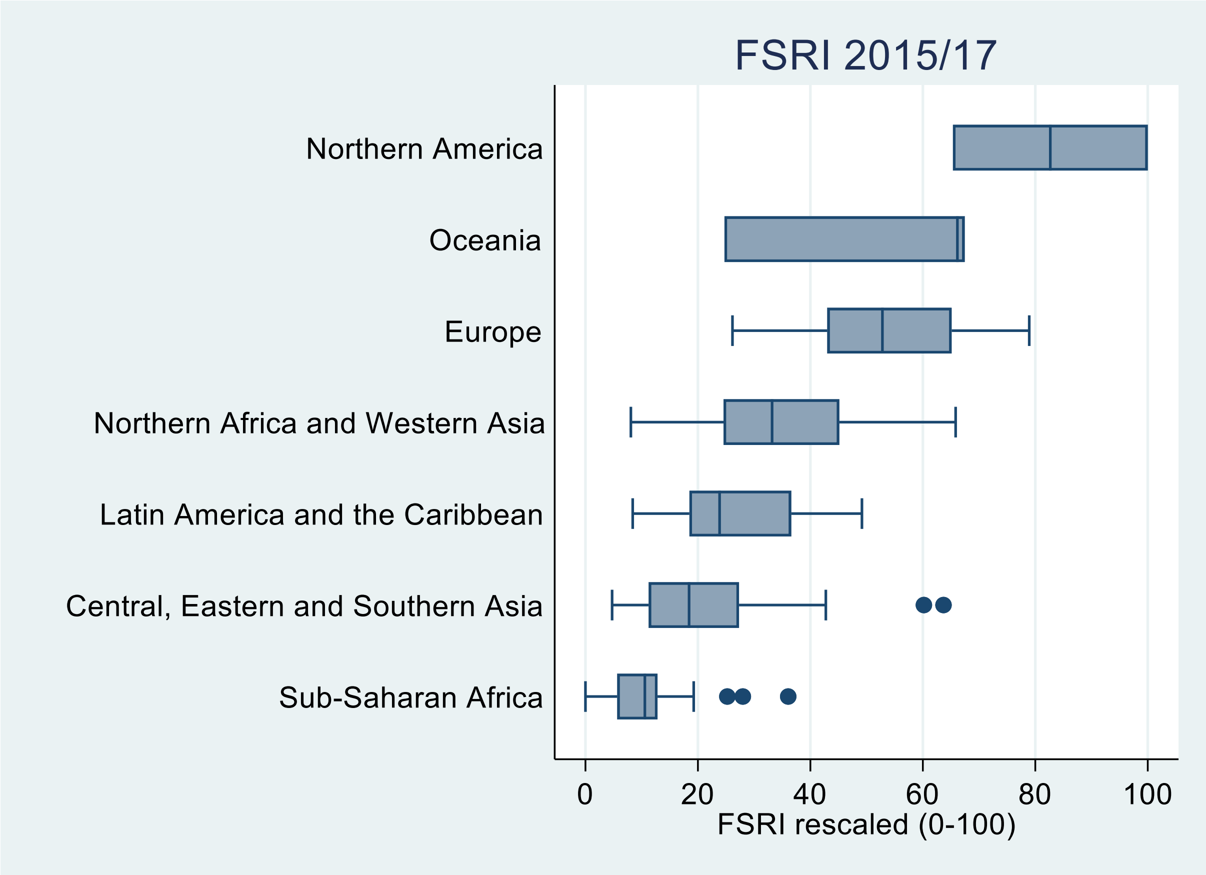
Figure 2. World map of the food system resilience (2015/17)



Note: The Food System Resilience Index (FSRI) is missing for 49 countries, see Table A2 in the Annex for details.

Source: Author's own elaboration. Conforms to Map No. 4170 Rev. 19 UNITED NATIONS (October 2020).

Figure 3. Food System Resilience Index average by region

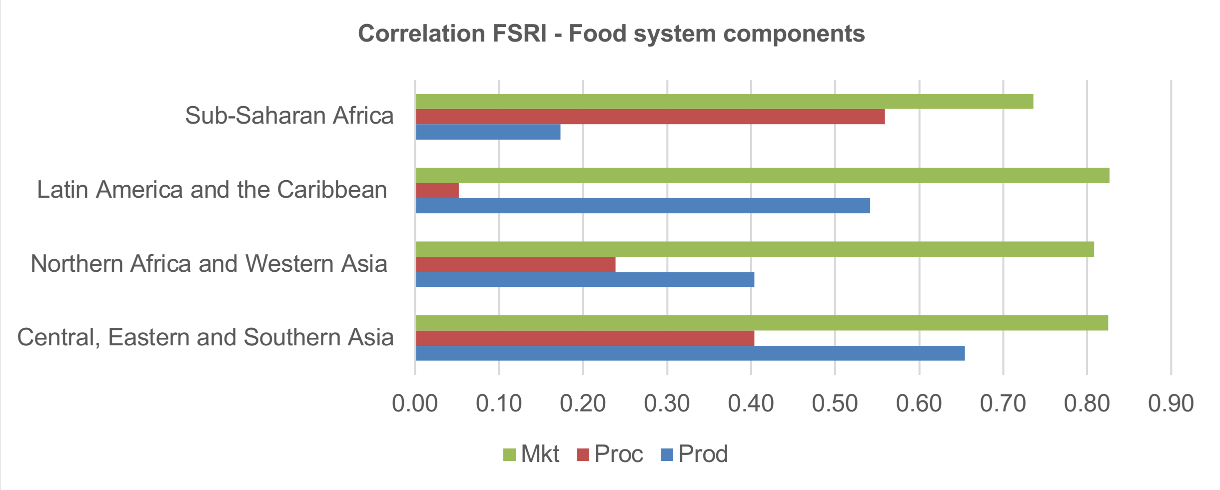


Notes: The figure shows the 2015/17 Food System Resilience Index (FSRI) for 136 countries: two in Northern America; 37 in Europe; three in Oceania; 18 in Northern African and Western Asia; 23 in Latin America and the Caribbean; 31 in sub-Saharan Africa and 22 in Asia. The outliers are Mauritius, South Africa and Botswana in sub-Saharan Africa; Japan and the Republic of Korea in Eastern Asia.

Source: Author's own elaboration.

Figure 4 shows the correlation of each pillar (production, processing, and markets) with the FSRI for the four regions where low- and middle-income countries predominate (Figure A3 shows the correlations when using the reduced model with two components). The horizontal axis is scaled from 0 to 1 with higher numbers indicating greater correlation. In all regions, correlations are strongest with the markets pillar. Food production is strongly correlated with the FSRI in Central, Eastern and Southern Asia and to a lesser extent in North Africa and Western Asia, Latin America and the Caribbean. Food production is weakly correlated with the FSRI in sub-Saharan Africa; by contrast, the correlation between the processing sector and FSRI is highest in sub-Saharan Africa. Correlations with the processing sector and FSRI are low in Latin America and the Caribbean and in North Africa and Western Asia. In Latin America and the Caribbean, this appears to reflect high levels of losses in cereals and fruits, but some of the products are grown for export with only limited correlation with domestic food security. In the case of North Africa and Western Asia, fruit losses are low which may account for the low correlation with domestic food security.

Figure 4. Contribution of the food system components to the overall resilience



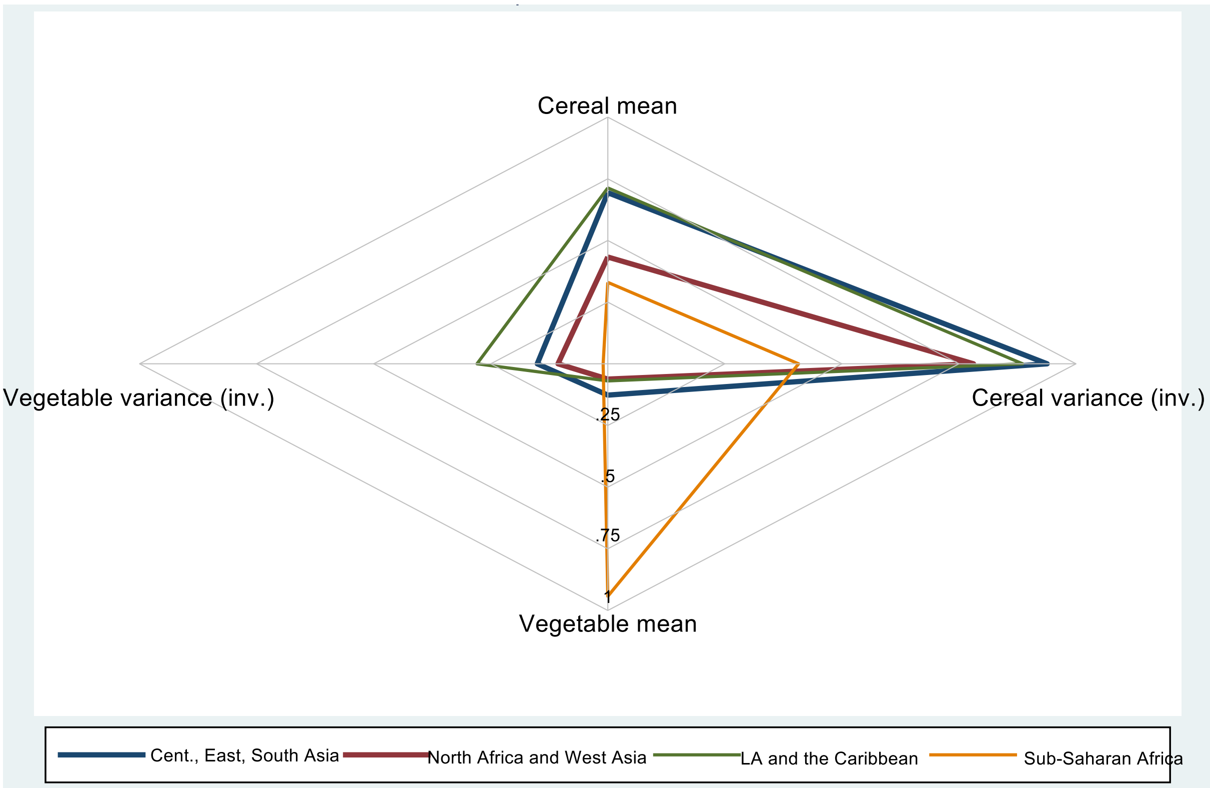
Correlation Food System Resilience Index (FSRI) and food system components				
	Central, Eastern and South Asia	**North Africa and Western Asia**	**Latin America and the Caribbean**	**Sub-Saharan Africa**
Food production	0.6546	0.4042	0.5414	0.1734
Food processing	0.4038	0.2389	0.0521	0.5589
Food markets	0.8248	0.8081	0.8262	0.7361
Observations	22	18	23	31

Source: Author's own elaboration.

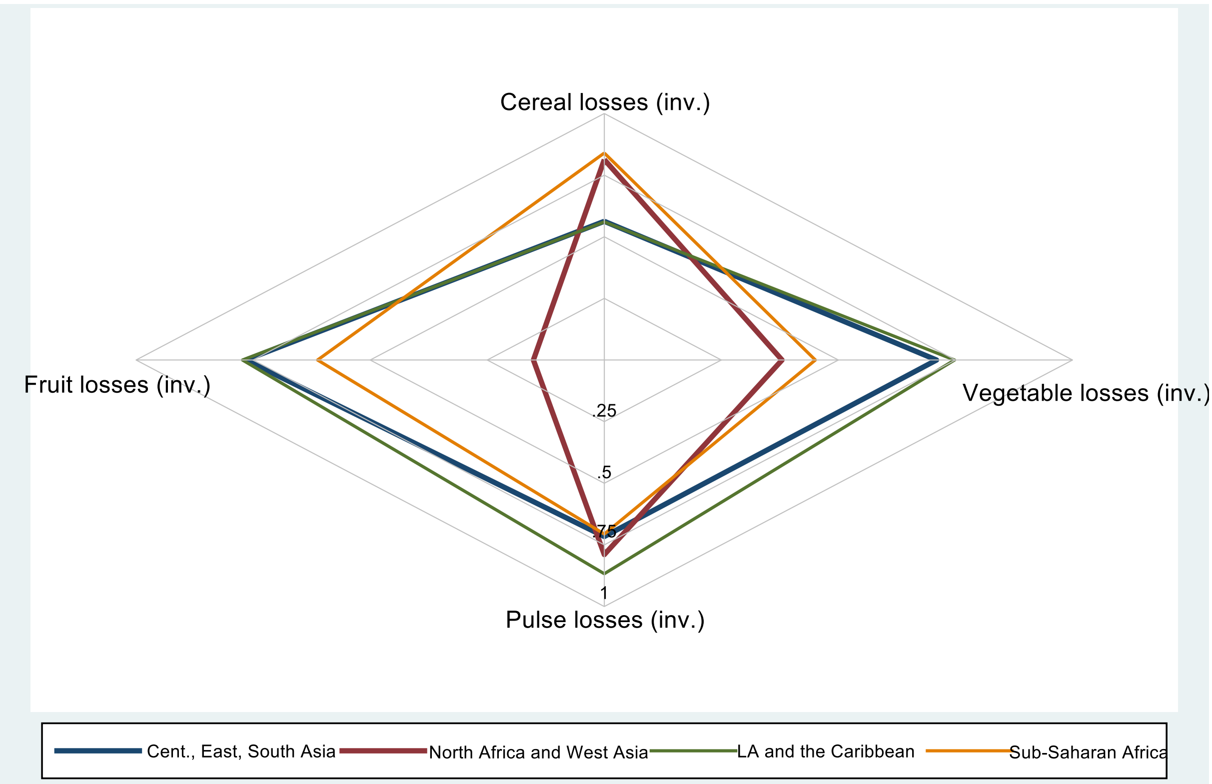
Figure 5 shows the correlations between each component of the food system and the individual indicators that make up this component. We use diamond shapes where we have four indicators (production, processing) and triangles where we have three indicators (markets). In these shapes, a longer distance from the centroid, the greater the correlation between the indicator and the measure of resilience for its component of the food system. Variables that are expressed as variances (such as the variance of cereal and vegetable production) are inverted so as to generate positive correlations. Where the shapes are symmetric around the centroid, the correlations of each indicator with the component's resilience are similar.

Figure 5. Food system components' correlations by region

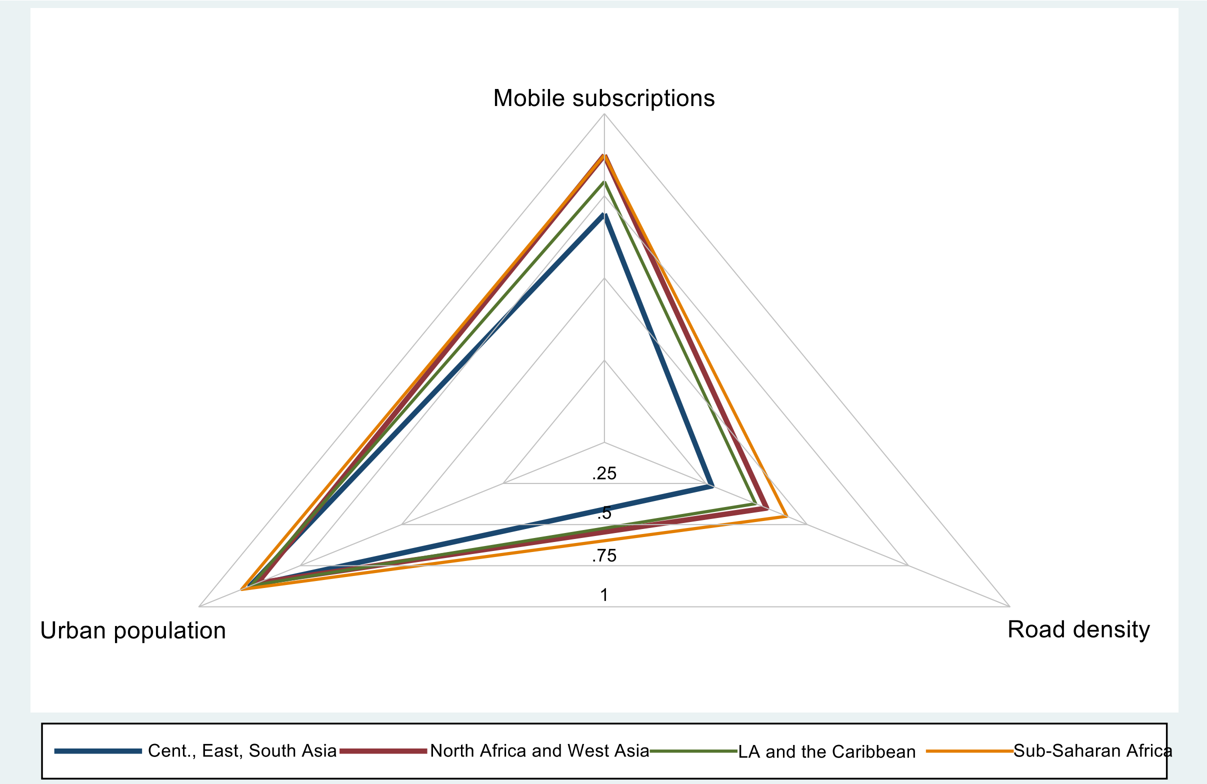
a. Food production correlations



b. Food processing correlations



c. Food markets correlations



Source: Author's own elaboration.

The first panel of Figure 5 shows that in three regions – Central, Eastern and Southern Asia, Northern Africa and Western Asia and Latin America and the Caribbean – production resilience is highly correlated with the mean and variance of cereals production. These correlations also exist in sub-Saharan Africa, but their magnitude is smaller (especially the cereal and vegetable variances that proxy the stability of the production); conversely mean vegetable production is more highly correlated with food production resilience in sub-Saharan Africa that elsewhere. In all regions, the inverse of losses in all food groups is correlated with resilience of the processing sector. In all regions, markets resilience is highly correlated with urbanization and mobile phone subscriptions. Road density has the (relatively) weakest correlations with market resilience.

5 Conclusions

As a way to formulate strategy, and as a topic of research, the food systems concept has attracted a considerable amount of attention. While the food systems concept has been in circulation for many years, the 2021 United Nations Food Systems Pre-summit has spotlighted its standing on the world stage. The interest in food systems can be attributed to the opportunity to better understand and represent the array of factors that explain food security in a more comprehensive and holistic manner. The value-added proposition of food systems resilience is that the ability to respond to shocks and stressors may be incorporated into such explanations. The qualities that make food system resilience attractive, however, also make it difficult to model in empirical terms. The array of variables, interactions among variables, and data limitations constrain make the task of modelling food systems resilience complex. From a theoretical perspective, one potential limitation of this type of analysis is the combined use of *national* and *international* data (Rose and Spiegel 2011). In fact, food system resilience is estimated using national characteristics, and is potentially affected by international level shocks and disturbances. From an empirical perspective, the fundamental challenge of work on food systems resilience is to create a feasible path through this complexity. In response to this challenge, this paper conceptualizes a way to empirically model food system resilience, by combining analytical tools provided RIMA with a selection of empirical procedures to estimate production, markets, and processing. Food systems-oriented data were then drawn upon to model food systems resilience at the country level.

There are three major findings. First, we have demonstrated the feasibility of an approach to measure food system resilience at the county level. This can be counted as technical contribution that may be built upon and further developed. Second, on a more substantive level the results demonstrated the way in which different countries exhibited different levels of resilience. Clustering countries into regions, sub-Saharan African countries exhibited the lowest levels of food systems resilience. Countries in Central, Eastern and Southern Asia ranked second lowest with countries in Latin America and the Caribbean ranking just above the third from the bottom. Countries in Northern Africa and Western Asia rank just below Europe. Northern America and Oceania placed first and second on food systems resilience, respectively. Third, the results demonstrated that the different components of food systems contributed to food systems resilience in different ways with markets and food production exerting the strongest influence for the overall model. Interestingly, the results by region, with a focus on developing countries, showed that markets made a greater contribution than production.

We conclude by offering the simple observation that conceptual models that illustrate the complexity of food systems in graphic representations are plentiful. Testable empirical models are less common. Our work is offered as a first approximation of how food system resilience may be conceptualized and modelled in empirical work. What is needed to advance work on food systems resilience is a focused and sustained programme of research that can generate the evidence on which more effective strategies for food and nutrition security in shock-prone contexts may be achieved.

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Annex

Table A1. Summary statistics of indicators employed for estimating Food System Resilience Index

Variable	Mean	Std. Dev.
Cereal yield (kg per hectare)	3 523.7	2 001.5
Cereal variance (kg per hectare)	162 123.6	336 803.4
Vegetable yield (tonnes per hectare)	18.0	10.3
Vegetable variance (Tons per hectare)	5.4	41.3
Cereal losses (%)	4.4	3.3
Vegetable losses (%)	8.5	3.8
Pulse losses (%)	4.7	4.9
Fruit losses (%)	8.9	9.1
Mobile cellular subscriptions (per 100 people)	111.5	30.4
Road density (meters per sq. kilometre of land)	0.6	1.1
Urban population (% of tot. population)	60.7	20.9
Prevalence of undernourishment (probability)	8.5	10.2
Consumption expenditure (2011 PPP)	10 222.1	7 929.3

Note: Data are three-year averages, 2015–2017 available for 136 countries.

Source: Author’s own elaboration.

Table A2. Country with missing data

Country	Missing indicators (2015/17)
Antigua and Barbuda	Pulse loss – only year 2012; undernourishment*
Bahamas	Pulse loss (1988-2009); undernourishment*
Bhutan	All loss*; undernourishment*
Brunei Darussalam	All loss*
Burundi	All loss*; undernourishment*
Central African Republic	Undernourishment – only year 2000
Comoros	All loss*; undernourishment*
Democratic Republic of the Congo	All loss*; veg. yield*; undernourishment*
Djibouti	Undernourishment – only year 2000
Dominica	Pulse loss – only year 1995; consumption*
Eritrea	All loss*; consumption; undernourishment*
Grenada	Consumption*; undernourishment*
Guinea	Undernourishment – only year 2000
Guinea-Bissau	Undernourishment – only year 2000
China, Hong Kong SAR	Road density*
Iceland	Cereal yield*; all loss*
Kiribati	Cereal yield*; pulse loss*; road density*
Democratic People's Republic of Korea	Consumption*
Lao People's Democratic Republic	Undernourishment – only year 2000
Libya	All loss*; consumption*; undernourishment*
China, Macao SAR	Cereal yield*; vegetable yield*; road density*
Maldives	Undernourishment – only year 2000; road density*
Micronesia (Federated States of)	Cereal and vegetable yield*; road density*; all loss*; consumption*; undernourishment*
Niger*	Undernourishment - only year 2000
Palestine*	All loss*; vegetable yield*; undernourishment*
Papua New Guinea	All loss*; consumption*; undernourishment*
French Polynesia	Cereal yield*; mobile subscriptions;
Puerto Rico	All loss*; undernourishment*
Qatar	All loss*; undernourishment*
Republic of Moldova	Undernourishment*
Saint Kitts and Nevis	Cereal yield*; all loss*; undernourishment*
Saint Lucia	Cereal yield*; consumption – only year 2011; undernourishment*
Samoa	Cereal yield*; pulse loss*; consumption*
Sao Tome and Principe	Consumption*
Solomon Islands	Consumption*
Somalia*	All loss*; undernourishment*
South Sudan*	All loss*; undernourishment*
Saint Vincent and the Grenadines	Consumption*
Suriname	Consumption – only year 2010
Syrian Arab Republic	All loss*; consumption*; undernourishment*

Country	Missing indicators (2015/17)
Tajikistan	Undernourishment*
Trinidad and Tobago	Consumption*
Turkmenistan	Consumption – only years 2010 and 2011
Uganda	Undernourishment – only year 2000
Vanuatu	Pulse loss*; consumption (2004-2014)
Venezuela (Bolivarian Republic of)**	Consumption (1998-2014)
Yemen**	Consumption (only for 1998, 2005, 2014); undernourishment (only year 2000)
Zambia	Undernourishment – only year 2000
Zimbabwe	Undernourishment – only year 2000

Notes: Total countries with missing indicators: 49. * Indicators not available for the entire time-series. ** Global Network Against Food Crises, the EU-FAO Partnership Programme.

Source: Author's own elaboration.

Table A3. FSRI by country and MIMIC model specification

	Model with 3 food system components	Model with 2 food system components
	2015/17	2015/17
Northern America		
Canada	66.596	66.758
United States of America	100.000	100.000
Europe		
Albania	29.220	29.944
Austria	72.799	72.954
Belarus	42.000	42.745
Belgium	73.793	73.152
Bosnia and Herzegovina	33.861	34.420
Bulgaria	35.681	36.420
Croatia	48.512	48.204
Czech Republic	52.618	52.779
Denmark	66.629	66.947
Estonia	50.092	49.253
Finland	64.955	65.295
France	63.195	63.541
Germany	73.411	73.538
Greece	55.509	56.199
Hungary	45.603	45.545
Ireland	65.917	65.781
Italy	65.065	64.077
Latvia	48.822	48.362
Lithuania	53.915	54.837
Luxembourg	77.851	76.534
Macedonia	27.207	27.779
Malta	54.183	53.964
Montenegro	44.288	44.376
Netherlands	68.495	67.794
Norway	70.042	69.762
Poland	52.114	52.672
Portugal	62.605	62.118
Romania	44.465	43.972
Russian Federation	48.525	47.945
Serbia	28.813	29.314
Slovakia	36.747	37.026
Slovenia	51.523	51.420
Spain	62.584	62.283
Sweden	64.690	65.314
Switzerland	79.722	79.119
Ukraine	29.892	30.317

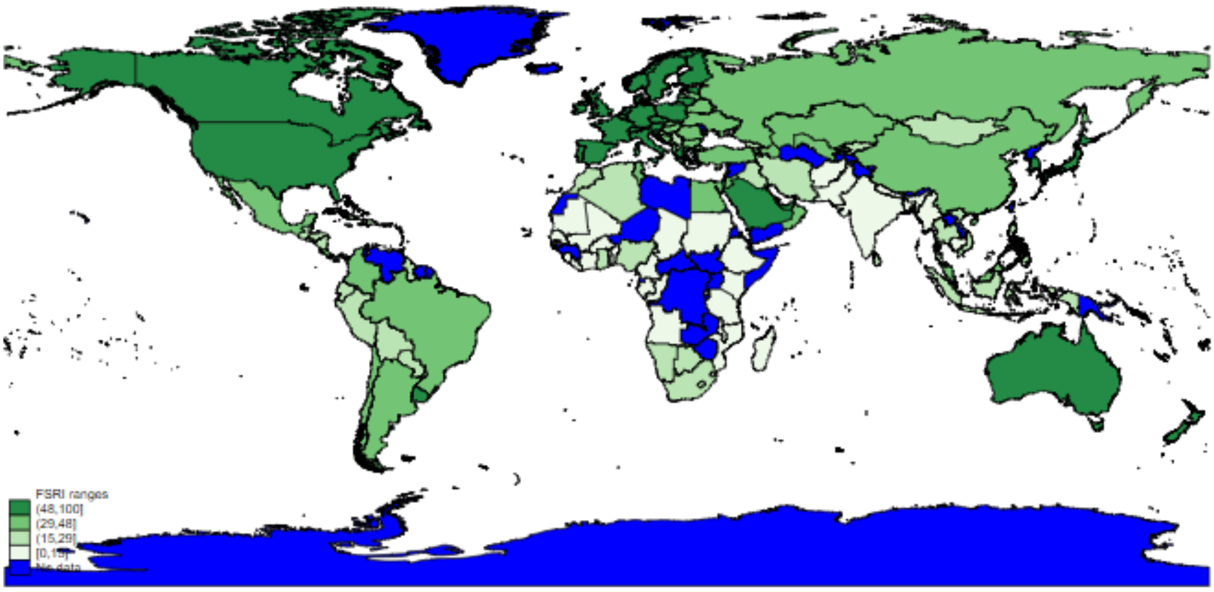
	Model with 3 food system components	Model with 2 food system components
	2015/17	2015/17
United Kingdom	72.152	71.700
Oceania		
Australia	67.324	67.766
Fiji	26.601	25.641
New Zealand	67.384	68.017
Northern African and Western Asia		
Algeria	23.691	24.030
Armenia	32.641	32.401
Azerbaijan	34.658	35.006
Cyprus	43.035	41.872
Egypt	31.817	32.200
Georgia	26.112	25.675
Iraq	21.187	21.068
Israel	57.625	57.411
Jordan	34.918	35.219
Kuwait	66.058	66.222
Lebanon	38.409	37.948
Morocco	21.839	22.606
Oman	37.214	36.003
Saudi Arabia	49.336	49.659
Sudan	9.679	10.004
Tunisia	30.206	31.200
Turkey	46.677	47.369
United Arab Emirates	54.827	55.390
Latin America and the Caribbean		
Argentina	44.815	45.865
Barbados	28.573	26.719
Belize	14.603	15.165
Bolivia	19.134	19.669
Brazil	41.128	42.258
Chile	46.543	47.193
Colombia	30.352	30.545
Costa Rica	39.861	40.302
Cuba	24.291	24.852
Dominican Republic	28.697	29.170
Ecuador	20.883	21.226
El Salvador	24.156	25.058
Guatemala	19.194	19.997
Guyana	20.759	20.111
Haiti	9.886	10.186
Honduras	17.347	17.938
Jamaica	21.681	22.004
Mexico	32.260	32.967

	Model with 3 food system components	Model with 2 food system components
	2015/17	**2015/17**
Nicaragua	20.433	21.306
Panama	37.896	37.326
Paraguay	24.457	25.203
Peru	26.461	27.396
Uruguay	49.653	50.996
Central, Eastern and Southern Asia		
Afghanistan	6.322	6.555
Bangladesh	12.469	12.421
Brunei	n/a	41.127
Cambodia	11.767	12.265
China	32.556	33.175
India	12.560	12.818
Indonesia	22.961	23.789
Iran	26.185	26.884
Japan	64.641	64.589
Kazakhstan	44.440	44.362
Korea Rep	61.075	61.190
Kyrgyzstan	17.529	17.234
Malaysia	41.415	41.204
Mongolia	21.085	19.739
Myanmar	9.379	9.643
Nepal	11.630	12.053
Pakistan	12.137	12.303
Philippines	19.296	19.138
Sri Lanka	19.508	19.817
Thailand	25.436	26.235
Timor Leste	9.916	10.258
Uzbekistan	29.943	29.855
Vietnam	18.422	18.716
Sub-Sahara Africa		
Angola	11.819	12.410
Benin	10.731	11.305
Botswana	26.988	26.445
Burkina Faso	7.090	7.533
Cameroon	11.877	12.610
Cape Verde	19.586	17.765
Chad	3.912	4.187
Congo	14.880	13.294
Cote d'Ivoire	13.744	14.603
Ethiopia	4.421	4.590
Gabon	12.361	13.065
Gambia	16.810	17.366
Ghana	14.329	13.943

	Model with 3 food system components	Model with 2 food system components
	2015/17	**2015/17**
Kenya	9.905	10.233
Lesotho	9.872	9.187
Liberia	9.767	9.520
Madagascar	6.035	6.439
Malawi	0.000	0.000
Mali	12.523	13.094
Mauritania	12.316	12.621
Mauritius	37.862	35.577
Mozambique	5.340	5.512
Namibia	20.425	20.859
Nigeria	13.881	14.607
Rwanda	5.515	5.757
Senegal	12.760	12.632
Sierra Leone	8.479	9.084
South Africa	28.681	29.405
Swaziland	13.680	13.745
Tanzania	6.453	6.999
Togo	6.732	7.316
Observations	136	137

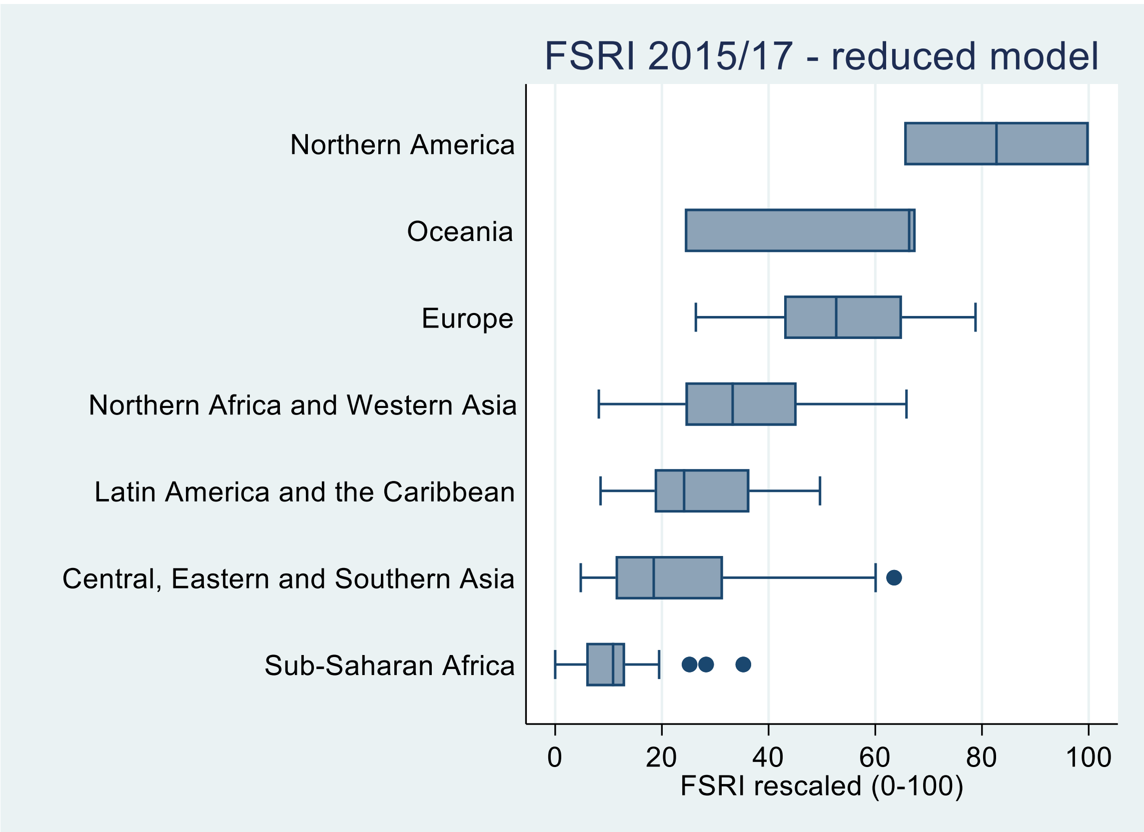
Source: Author's own elaboration.

Figure A1. World map of the food system resilience (2015/17) – reduced model with two food system component



Source: Author's own elaboration. Conforms to Map No. 4170 Rev. 19 UNITED NATIONS (October 2020).

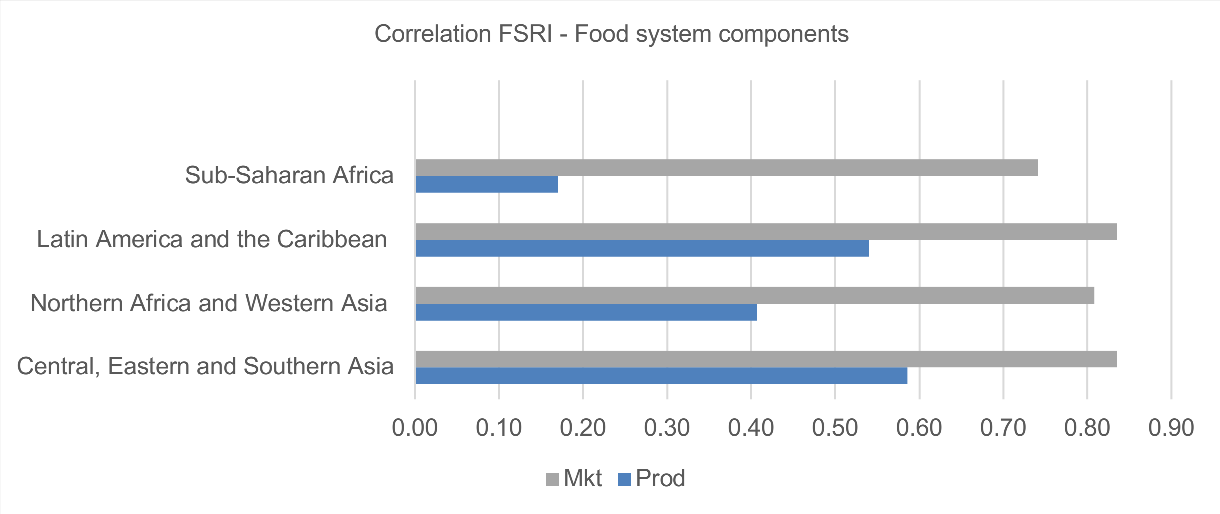
Figure A2. Food System Resilience Index by region – reduced model with two food system component



Note: The figures shows the 2015/17 FSRI estimated from a reduced model for 137 countries.

Source: Author's own elaboration.

Figure A3. Contribution of the food system components to the overall resilience – reduced model



Correlation Food System Resilience Index (FSRI) and food system components				
	Central, Eastern and South Asia	**North Africa and Western Asia**	**Latin America and the Caribbean**	**Sub-Saharan Africa**
Food production	0.5856	0.4069	0.5399	0.1702
Food markets	0.8351	0.8083	0.8353	0.7409
Observations	23	18	23	31

Source: Author’s own elaboration.

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