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**Rethinking the Measurement of Resilience for  
Food and Nutrition Security**

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## Abstract

This paper presents a novel framework for assessing resilience in food systems, focusing on three dynamic metrics: return time, magnitude of deviation, and recovery rate. Traditional resilience measures have often relied on static and composite indicators, creating gaps in understanding the complex responses of food systems to shocks. This framework addresses these gaps, providing a more nuanced assessment of resilience in agrifood sectors. It highlights how integrating dynamic metrics enables policymakers to design tailored, sector-specific interventions that enhance resilience. Recognizing the data intensity required for these metrics, the paper indicates how emerging satellite imagery and advancements in artificial intelligence (AI) can make data collection both high-frequency and location-specific, at a fraction of the cost of traditional methods. These technologies facilitate a scalable approach to resilience measurement, enhancing the accuracy, timeliness, and accessibility of resilience data. The paper concludes with recommendations for refining resilience tools and adapting policy frameworks to better respond to the increasing challenges faced by food systems across the world.

**Key words:** Resilience, food security, metrics, shocks, recovery rate, return time, magnitude

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## 1. Introduction

Food security, defined as the availability of and access to sufficient, safe, and nutritious food to meet the dietary needs of a population, is a critical issue that underpins global health, economic stability, and social harmony. The concept is fundamental not only to human survival but also to the overall well-being of societies, impacting everything from economic productivity to social stability. The World Health Organization (WHO) emphasizes that food security is essential for human health, as malnutrition and hunger can lead to long-term developmental challenges and societal disruptions (FAO 2016). Achieving food security is particularly challenging in a world facing a myriad of shocks and stresses, including climate change, economic instability, political unrest, and health pandemics like COVID-19. These challenges have heightened the need for resilient food systems that can withstand, adapt to, and recover from such disruptions.

Resilience, in the context of food security, refers to the capacity of food systems to absorb shocks, adapt to changing conditions, and transform in ways that reduce future vulnerabilities while maintaining core functions. A resilient food system is crucial to ensure that populations have continuous access to food, even in the face of adverse events. This concept has gained increasing attention in recent years, particularly as global food systems are being tested by more frequent and severe disruptions. For instance, climate change has introduced new levels of uncertainty into agricultural production, with altered precipitation patterns, more frequent extreme weather events, and rising temperatures posing significant threats to crop yields and food availability (FAO 2022). Similarly, economic crises and political instability can disrupt supply chains, leading to increased food prices and reduced access, further exacerbating food insecurity (Fanzo et al. 2021).

While the importance of resilience in food systems is well recognized, the tools and metrics used to measure resilience remain underdeveloped and are often criticized for their inability to capture the full spectrum of resilience attributes. Traditional resilience metrics have typically focused on general indicators such as the stability of food supply or income levels, often overlooking critical components that determine how effectively a system can recover from a shock. These components include return time (the time it takes for a system to return to equilibrium after a disturbance), magnitude of deviation (the extent to which a system is pushed out of equilibrium), and recovery rate (the speed at which a system recovers after a shock) (Béné et al. 2019; Tendall et al. 2015).

The limitations of existing resilience metrics can lead to significant policy biases. For example, a focus solely on the return time might lead to policies that prioritize quick fixes over sustainable solutions, while neglecting the magnitude of the initial disruption or the rate at which recovery occurs can result in interventions that fail to address the root causes of vulnerability. This gap in current resilience assessment tools underscores the need for a more integrated approach that can provide a comprehensive understanding of how food systems respond to shocks and stresses (Herrero et al. 2021).

A key challenge in resilience measurement is the complexity of food systems, which are influenced by a wide range of biophysical, economic, and social factors. Existing metrics often fail to account for the dynamic and interconnected nature of these systems, leading to oversimplified assessments that do not fully capture the nuances of resilience. For instance,

metrics that rely heavily on economic indicators may not adequately reflect the social or environmental dimensions of resilience, such as community support networks or ecosystem health, which are crucial for long-term food security (Béné et al. 2020). Moreover, many resilience metrics are static, providing a snapshot of resilience at a single point in time, rather than capturing the dynamic processes of adaptation and transformation that are essential for building long-term resilience (Grafton et al. 2021).

The relevance of this paper is underscored by the urgent need for more effective tools to assess and enhance food system resilience. As the frequency and severity of disruptions increase, so does the importance of ensuring that food systems are not only able to recover from shocks but also adapt to changing conditions in a way that reduces future vulnerabilities. Policymakers, researchers, and practitioners are increasingly confronted with the challenge of designing interventions that are both effective in the short term and sustainable in the long term. However, existing resilience measurements often rely on oversimplified or incomplete metrics that do not fully capture the diverse ways in which food systems respond to and recover from disturbances. By focusing on the integration of return time, magnitude of deviation, and recovery rate, this paper provides a more comprehensive framework for resilience assessment that can better inform policy decisions and intervention strategies.

One of the key contributions of this paper is its emphasis on the need for a balanced and comprehensive approach to resilience assessment. The analysis reveals the risks of policy biases that can arise from relying on a single resilience metric. For example, a policy that prioritizes reducing return times without considering the magnitude of deviation might lead to quick recoveries that fail to address the underlying vulnerabilities exposed by certain shocks. Similarly, focusing on recovery rates without tackling the root causes of deviations can result in cyclical crises, in which the same weaknesses are repeatedly exploited by subsequent disturbances. By integrating all three resilience metrics, the paper highlights the importance of developing policies that are both holistic and tailored to the specific challenges faced by different food system components.

The novelty of this paper lies not only in its comprehensive framework for resilience measurement but also in its practical implications for policymaking. While each of the resilience metrics—return time, magnitude of deviation, and recovery rate—has been studied individually, this paper is among the first to systematically combine them into a cohesive framework. This integrative approach allows for a more holistic assessment of food system resilience, providing policymakers with the tools they need to develop interventions that are both effective and sustainable. The paper goes beyond theoretical analysis by offering tailored policy recommendations based on the distinct resilience attributes of different food products, such as food, meat, and cereals. This specificity is a novel aspect of the paper, as it provides actionable insights that can be directly applied to enhance resilience in targeted sectors.

By leveraging satellite data, which provides high frequency, spatially resolved observations, coupled with AI's capacity for rapid data processing and pattern recognition, it is now feasible to track resilience indicators such as return time, magnitude of deviation, and recovery rate at a significantly reduced cost. This technological integration offers a pathway to scalable and cost-effective resilience measurement, enhancing data availability, accuracy, and timeliness—key aspects for proactive policymaking in food security.

The core of the paper is divided into several key sections. First, the paper provides an overview of existing metrics. Next, the paper dives into three resilience attributes: return time, magnitude of deviation, and recovery rate. These metrics are essential for understanding how food systems respond to and recover from shocks. The paper then illustrates these concepts using a dynamic system model, providing empirical analysis and deriving relevant resilience metrics.

The discussion and policy implications section delve into the practical implications of these metrics, analyzing their application to food price indices, meat price indices, and cereals price indices. Finally, the paper concludes by emphasizing the need for targeted, metric-based policy interventions to strengthen the resilience of global food systems.

## **2. Data needs and limitations in resilience measurement**

In the study of resilience, particularly in food systems, data play a critical role in determining how systems withstand, respond to, and recover from shocks. Accurate measurement of resilience metrics such as return time, magnitude of deviation, and recovery rate is contingent on the availability and quality of relevant data. Yet, despite the increasing focus on resilience, many challenges remain concerning the types of data required, their accessibility, and their limitations in providing a comprehensive understanding of food system resilience. This paper explores the key data needs and limitations that influence the accuracy and effectiveness of resilience assessments in food systems, emphasizing the complexity of this emerging field.

### *Data needs in resilience assessment*

One of the foremost requirements for assessing resilience is the availability of high-frequency data that capture system dynamics over time. Food systems are inherently volatile and subject to frequent disruptions, including climate events, market fluctuations, and sociopolitical instability. To adequately measure the response of food systems to such disturbances, it is essential to collect data at frequent intervals. Time series data on food prices, agricultural outputs, and household consumption are vital for tracking how quickly a system stabilizes after a shock (Béné et al. 2019). Granular data also allow for more nuanced insights into resilience, such as identifying specific bottlenecks or inefficiencies that hinder recovery.

Moreover, resilience is a multifaceted concept, and as such, it requires multidimensional data that reflect the diverse factors influencing system performance. Economic data, such as income levels, market access, and food affordability, need to be complemented by social data that capture the strength of community networks and the level of household support systems. Biophysical factors, including soil health, water availability, and climate variability, also play a crucial role in determining the resilience of agricultural systems (Fanzo et al. 2021). The interaction of these various dimensions—economic, social, and environmental—must be accounted for to build a comprehensive picture of resilience.

In addition to being multidimensional, resilience data must also be context specific. The factors that determine resilience vary significantly across different geographical and socioeconomic contexts. For example, smallholder farmers in sub-Saharan Africa may face entirely different resilience challenges than large-scale agricultural producers in Europe or North America. These food systems' vulnerability to environmental shocks such as droughts or floods depends on local conditions such as climate, infrastructure, and policy frameworks (Herrero et al. 2021).

Therefore, localized data that reflect these diverse realities is essential for tailoring resilience-building strategies to specific regions and populations.

#### *Data limitations in resilience measurement*

While the need for robust data is clear, several significant limitations constrain the ability to accurately measure resilience. A primary challenge is data availability and accessibility. In many regions, particularly in low-income or rural areas, data collection infrastructure is either underdeveloped or lacking entirely. This results in significant gaps in the data available for resilience assessments, especially household-level information on food security, agricultural productivity, and market access (Smith and Frankenberger 2018). Even when data are collected, access may be restricted because of bureaucratic barriers, political sensitivities, or proprietary constraints. As a result, resilience assessments often have to rely on incomplete datasets, which can lead to inaccurate or biased conclusions.

Another major limitation is the quality and accuracy of available data. In many cases, data on key resilience indicators may be subject to errors or inconsistencies. For example, self-reported surveys on household food security may reflect recall bias or social desirability bias, in which respondents may underreport instances of food insecurity because of stigma or embarrassment (Grafton et al. 2021). Similarly, official statistics on agricultural yields or food prices may be inaccurate because of political manipulation, especially in countries experiencing economic or political instability. These issues of data quality can undermine the reliability of resilience assessments and lead to flawed policy recommendations.

The issue of temporal and spatial data gaps also poses a significant challenge. Resilience is a dynamic process that involves adaptation and transformation over time, yet much of the data used in resilience assessments are static, providing only a snapshot of the system at a particular point in time. This static nature of data fails to capture the evolving nature of resilience and can overlook important trends in how food systems recover from shocks (Béné et al. 2020). In addition, spatial gaps in data coverage mean that certain regions, particularly rural or underserved areas, may lack the detailed data necessary for accurate resilience assessments. This is particularly problematic in regions that are highly vulnerable to climate change, where the need for resilience-building is most urgent.

Another key limitation is the lack of standardization in resilience metrics. Resilience is a complex, multidimensional concept, and different studies or organizations often use different indicators or frameworks to measure it. For instance, one study may emphasize economic indicators such as income stability, while another focuses on social resilience factors like community cohesion (Tendall et al. 2015). This lack of consistency makes it difficult to compare resilience assessments across different contexts or to aggregate findings in a way that informs global resilience-building efforts. Without a standardized set of metrics, the field risks fragmentation, which can hinder progress in developing effective, scalable interventions.

Furthermore, certain aspects of resilience, particularly those related to social and community-level dynamics, are inherently difficult to quantify. For example, social capital and community resilience—including the strength of informal safety nets, the ability of communities to self-organize, and the level of trust within social networks—are critical for resilience but are challenging to measure with conventional data collection methods. While qualitative data such as

interviews or focus groups can provide valuable insights into these factors, such methods are time-consuming, resource intensive, and difficult to scale. As a result, these important dimensions of resilience are often underrepresented in formal assessments (Béné et al. 2019).

### **3. Overview of current metrics**

Resilience metrics have become vital tools in understanding how food systems cope with and recover from shocks. Metrics such as the Food Security and Nutrition Resilience Index (FSNRI), the Resilience Capacity Index (RCI), and the Resilience Index Measurement and Analysis (RIMA) have made valuable contributions by offering a broad assessment of resilience through various indicators. However, despite their usefulness, these existing resilience metrics fall short in capturing key resilience attributes, specifically return time, magnitude of deviation, and recovery rate. These attributes are crucial for a more nuanced and accurate measurement of how food systems recover from disturbances. This section will elaborate on the limitations of these popular metrics and why they fail to fully encapsulate these critical dimensions.

#### *Food Security and Nutrition Resilience Index (FSNRI)*

The FSNRI, developed by the Food and Agriculture Organization of the United Nations (FAO), combines a range of indicators related to food availability, access, utilization, and stability to assess the resilience of food systems. While comprehensive in scope, one of its main limitations is that it does not fully capture the temporal dimension of resilience—specifically, the concept of return time. Return time refers to the period it takes for a system to recover after a shock. The FSNRI focuses largely on static measures of food security, such as the stability of food supply, but does not measure how quickly a food system can bounce back after a disruption, such as a drought or market shock (FAO 2016).

Moreover, the FSNRI does not provide an in-depth assessment of the magnitude of deviation—the extent to which a system is displaced from its equilibrium state during a disturbance. By focusing more on overall food security indicators, the FSNRI may obscure the severity of the immediate impact of shocks, which is critical for understanding the depth of vulnerability. Similarly, recovery rate, or the speed at which a system returns to equilibrium, is not explicitly measured in the FSNRI. The index offers a broad view of food system stability but lacks the tools to assess how resilient the system is in terms of rapid recovery, leaving significant gaps in how resilience is understood.

#### *Resilience Capacity Index (RCI)*

The RCI is based on three main dimensions—absorptive capacity, adaptive capacity, and transformative capacity—to assess the resilience of households and communities. While these dimensions are essential for understanding how systems deal with and respond to shocks, the RCI also has notable shortcomings in measuring return time, magnitude of deviation, and recovery rate.

Absorptive capacity captures a system’s ability to absorb shocks, but it does not measure how long it takes for the system to recover after absorbing the shock. The return time aspect remains

unaddressed, leaving a gap in understanding how long households or communities remain in a vulnerable state before returning to normal functioning (Smith and Frankenberger 2018).

Similarly, while the RCI accounts for the capacity to adjust or transform aftershocks, it fails to quantify the magnitude of deviation that households experience when exposed to disruptions. Knowing how far a system is displaced from its pre-shock state is essential for planning effective interventions, but the RCI provides only a general sense of a system's ability to adapt without quantifying the severity of the initial disruption. Additionally, the recovery rate, or the speed at which systems regain stability, is not explicitly captured by the RCI, making it difficult to assess how quickly communities or households can recover from shocks.

#### *Resilience Index Measurement and Analysis (RIMA)*

The FAO's RIMA offers a more focused approach by assessing four key pillars: income and food access, access to basic services, assets, and social safety nets. The RIMA is particularly valuable in rural and developing country contexts where vulnerability to food insecurity is high. However, like the FSNRI and the RCI, the RIMA does not effectively measure return time. The RIMA's focus on static indicators—such as the availability of assets and access to services—does not account for how quickly these elements are restored after a disturbance, leaving policymakers with little information on the duration of vulnerability (FAO 2016).

Moreover, while the RIMA is useful for identifying the determinants of resilience, it lacks a direct measurement of the magnitude of deviation. Understanding the severity of disruptions, such as how much household income or food access decreases during a crisis, is critical for designing targeted interventions. However, the RIMA does not offer a clear quantification of these deviations, leading to potential gaps in understanding the full impact of a shock. Similarly, the recovery rate is not adequately addressed in the RIMA. The speed at which households recover access to food, income, or basic services is not measured, leaving out a crucial aspect of resilience assessment.

#### *Livelihood Resilience Index (LRI)*

The LRI assesses the resilience of livelihoods, focusing on income diversification, access to markets, and the use of sustainable agricultural practices. While these indicators are important, the LRI shares the same limitations as other metrics in its failure to capture return time. The LRI does not track how long it takes for livelihoods to stabilize after a disruption, such as a drop in crop yields or a market collapse (FAO 2019).

Moreover, the LRI does not fully measure the magnitude of deviation in livelihoods caused by shocks. For example, a significant drop in income due to a climate-related disaster may not be adequately quantified, making it difficult to assess the severity of the disruption. The recovery rate is similarly underexplored, as the LRI does not assess the speed at which households can return to pre-shock income levels or regain market access after a crisis. This gap in measurement leaves out critical information on how quickly recovery efforts can take effect.

One of the overarching criticisms of these existing resilience metrics is that they tend to focus on static indicators rather than capture the dynamic nature of resilience. Resilience is not a fixed state but a process that involves adaptation, transformation, and recovery over time. Most metrics

provide a snapshot of food system or household conditions at a given point but fail to track how these conditions evolve during and after a shock (Grafton et al. 2021). This lack of dynamic assessment means that the temporal aspects of resilience—particularly return time and recovery rate—are often overlooked, leading to incomplete assessments of how resilient systems truly are.

Overall, while existing resilience metrics such as the FSNRI, RCI, RIMA, HDDS, and LRI provide valuable insights into food security and the capacity of systems to cope with shocks, they fall short in adequately measuring key resilience attributes such as return time, magnitude of deviation, and recovery rate. These attributes are critical for a more complete understanding of how food systems respond to and recover from disruptions. Without addressing these shortcomings, resilience assessments will continue to provide an incomplete picture, limiting the effectiveness of policy interventions aimed at building more resilient food systems.

#### **4. Return time, magnitude of deviation, and recovery rate: Why they matter**

Resilience in food systems is a multidimensional concept that can be deconstructed into three key components: return time, magnitude of deviation, and recovery rate. Each of these attributes provides a unique perspective on the resilience of food systems and households, offering critical insights into how these systems respond to and recover from shocks. Understanding these attributes is essential for developing effective strategies to enhance resilience and ensure food security in the face of various disturbances.

##### *4.1. Return time*

Return time in the context of resilience refers to the duration it takes for a system to revert to its equilibrium state after experiencing a disturbance. This concept is vital because it captures the temporal dimension of recovery, which is crucial for assessing how quickly a food system can stabilize after a shock. A system with a shorter return time is considered more resilient because it can rapidly restore its functions, ensuring that disruptions do not lead to prolonged periods of instability (Béné 2020). In food security, return time can be applied to various aspects, such as the recovery of crop yields, stabilization of food prices, and restoration of food supply chains following events like droughts, floods, or economic crises.

Measuring return time helps policymakers and practitioners identify vulnerabilities within food systems and implement timely interventions to enhance resilience. For example, long return times indicate prolonged recovery periods, which necessitate comprehensive, long-term strategies. Investing in agricultural infrastructure—such as irrigation systems and storage facilities—can significantly enhance resilience by ensuring water availability and reducing postharvest losses (World Bank 2007). Similarly, promoting sustainable agricultural practices improves soil health and water management, contributing to long-term resilience (Pretty et al. 2011). Strengthening social safety nets is also crucial to support vulnerable populations during extended recovery periods, thereby preventing food insecurity and malnutrition (Alderman and Hoddinott 2007).

In contrast, short return times reflect a system's ability to recover quickly from disruptions. Policies aimed at providing rapid support, such as emergency grants or low-interest loans, can help farmers resume production quickly, minimizing the impact of shocks (Carter et al. 2007).

Additionally, facilitating the quick distribution of food aid and agricultural inputs ensures that disruptions do not lead to prolonged food shortages (Devereux 2009). Efficient market linkages and supply chain management are also essential for restoring market functions rapidly (Pieters et al. 2013).

Several methodologies exist for measuring return time, including time series analysis, which tracks the recovery trajectory of key indicators such as crop yields, food prices, and household food consumption levels. For instance, Egamberdiev et al. (2023) use household food consumption data to assess return time following economic and climate shocks in Kyrgyzstan, finding that households with shorter return times were better able to maintain food security, underscoring the importance of rapid recovery.

Another approach involves resilience indices that incorporate return time as a component. For example, the RCI developed by Smith and Frankenberger (2018) includes return time alongside other factors such as absorptive and adaptive capacities. Although these metrics provide valuable insights, they also have limitations, particularly in low-resource settings where high-quality data may be scarce. Despite these challenges, return time remains a critical tool in resilience assessment.

#### *4.2. Magnitude of deviation*

Magnitude of deviation refers to the maximum extent to which a system deviates from its equilibrium state following a disturbance. In food security, this could manifest as significant changes in food availability, access, utilization, or stability due to shocks such as droughts, floods, economic downturns, or pandemics. This metric is crucial because it quantifies the severity of a disturbance's impact, providing a clear measure of how far the system is pushed from its normal functioning state.

Understanding the magnitude of deviation helps identify the most vulnerable aspects of a food system, enabling policymakers and practitioners to prioritize interventions and allocate resources more effectively to mitigate the adverse effects of shocks (Béné 2020). Large deviations often require immediate relief measures, such as strategic food reserves to stabilize prices and ensure a steady supply during disruptions (Lybbert and Sumner 2012). On the other hand, low deviations suggest a relatively stable food system, where policies can focus on maintaining this stability through support for small-scale farmers, improving their access to inputs and infrastructure (IFAD 2013).

Statistical measures such as standard deviation, variance, and coefficient of variation are commonly used to assess changes in key food security indicators before and after a disturbance. For example, Dagunga et al. (2023) use standard deviation to measure fluctuations in crop yields in smallholder farming systems following environmental shocks, finding that regions practicing agroecology exhibited lower deviations, indicating higher resilience.

Case studies further illustrate the application of magnitude of deviation metrics. In Bangladesh, Smith and Frankenberger (2018) used variance and standard deviation to measure household food security deviations following the 2014 floods, highlighting the vulnerability of poorer households. Similarly, a study in Kenya during the COVID-19 pandemic used the coefficient of

variation to assess fluctuations in food prices, revealing that urban areas were more resilient to economic impacts compared to rural areas (Merchant et al. 2022).

### *Recovery rate*

Recovery rate refers to the speed at which a system returns to its equilibrium state after experiencing a disturbance. This attribute is critical for understanding resilience because it captures the system's ability to restore functionality rapidly, thereby minimizing the duration and severity of disruptions. In the context of food security, a high recovery rate implies that food systems can quickly bounce back from shocks such as natural disasters, economic crises, or health pandemics, ensuring minimal impact on food availability, access, and stability (Béné 2020).

Recovery rate is often calculated using mathematical models that analyze system dynamics. For example, the dominant eigenvalue of the Jacobian matrix, evaluated at the equilibrium point, can indicate the rate at which the system's state variables return to equilibrium. A smaller dominant eigenvalue corresponds to a faster recovery rate, indicating a more resilient system (Scheffer et al. 2009).

Low recovery rates suggest slow adaptation and recovery, necessitating interventions that enhance response mechanisms. Enhancing agricultural extension services, for example, provides farmers with timely advice and support, improving their ability to respond to shocks (Anderson and Feder 2007). In contrast, high recovery rates suggest effective recovery processes that can be further optimized through strategies such as strengthening agricultural research, promoting value chain development, and fostering community-based resource management (Alston et al. 2010; Pretty and Ward, 2001).

Several methods exist to measure recovery rate, including time series analysis, where the speed of return to equilibrium is quantified by examining changes in key indicators over time. Smith and Frankenberger (2018) employ regression analysis to estimate the recovery speed for various food security indicators, finding that households with greater access to resources and support services exhibited faster recovery rates.

## **5. Illustration**

The notion of equilibrium in food systems, while complex and debated, is a useful construct for assessing resilience and stability. In this study, the long-run equilibrium is conceptualized as both a statistical central tendency (mean value of the indicator variable) and a desired state of the system. This approach is supported by theoretical and applied research that demonstrates the utility of equilibrium as an analytical tool in dynamic systems, including food and nutrition security.

The mean value, as a proxy for equilibrium, serves several purposes. First, it provides a baseline for quantifying deviations caused by shocks, facilitating consistent and comparable resilience metrics such as return time, magnitude of deviation, and recovery rate. Empirical studies underscore that while food systems are nonstationary and evolve over time, they often exhibit bounded fluctuations around a central tendency when observed over appropriate timescales

(Mezzenga 2007). This bounded variability reflects an inherent level of systemic stability, even in dynamic contexts.

Equilibrium can also represent a normative or desired state, aligning with sustainability and resilience goals in food systems. Gao et al. (2021) emphasize the importance of equilibrium as a target state for sustainable food production, balancing dietary needs, biodiversity, and self-sufficiency. Similarly, Xu et al. (2023) argue that optimizing food systems for sustainability inherently involves steering them toward desired equilibria.

While the equilibrium assumption simplifies the inherent complexity of food systems, it remains an effective analytical construct for resilience analysis. Future work could expand upon this by integrating adaptive baselines or equilibrium shifts that reflect evolving system dynamics and policy interventions.

To derive appropriate and robust metrics for resilience to shocks for food security, we use the basic characteristics of differential equations. We consider a dynamic system model that describes the state of food and nutrition security over time. We focus on three primary metrics: return time, magnitude of deviation, and recovery rate.

### *5.1. Model setup*

Let  $F(t)$  represent the state of food and nutrition security at time  $t$ . The dynamics of  $F(t)$  can be described by a differential equation incorporating a shock  $S(t)$  and a recovery function  $R(t)$ :

$$(1) \frac{dF(t)}{dt} = R(F(t)) - S(t)$$

where

- $R(F(t))$  is the recovery function, which depends on the current state  $F(t)$ .
- $S(t)$  is the shock function, which represents external disturbances affecting the system.

#### *Return time*

As explained in the previous section, the return time is the time it takes for the system to return to its equilibrium state after a shock. Let  $F_0$  be the equilibrium state of  $F(t)$  before the shock. When a shock  $S(t)$  occurs, the system deviates from  $F_0$ .

Assume the shock occurs at  $t = t_s$  and the system starts recovering at  $t = t_s + \Delta t$ . The return time  $T_r$  is defined as the time it takes for  $F(t)$  to return to  $F_0$ :

$$(2) T_r = \inf\{t > t_s : F(t) = F_0\}$$

#### *Magnitude of deviation*

The magnitude of deviation measures the maximum deviation of the system from its equilibrium state due to a shock. This is defined as:

$$(3) D = \max_{t \in [t_s, t_s + T_r]} |F(t) - F_0|$$

*Recovery rate*

The recovery rate quantifies how quickly the system returns to its equilibrium state after the shock. We define the recovery rate  $R_r(t)$  as:

$$(4) R_t(t) = -\frac{d}{dt} |F(t) - F_0|$$

The recovery rate must be non-negative, indicating the system's speed of recovery.

Let's consider a specific case in which the recovery function is linear and the shock is a delta function:

$$(5) R(F(t)) = -k(F(t) - F_0), \text{ where } k > 0 \text{ is the recovery rate constant.}$$

$$(6) S(t) = S_0 \delta(t - t_s), \text{ where } \delta(t - t_s) \text{ is the Dirac delta}^1 \text{ function and } S_0 \text{ is the magnitude of the shock.}$$

Equation 1 becomes:

$$(7) \frac{dF(t)}{dt} = -k(F(t) - F_0) - S_0 \delta(t - t_s)$$

The solution to this problem is:

$$(8) F(t) = F_0 + (F(t_s^-) - F_0)e^{-k(t-t_s)}$$

At  $t = t_s$ :

$$(9) F(t_s^+) = F(t_s^-) - S_0$$

Here,  $F(t_s^-)$  is the state just before the shock, and  $F(t_s^+)$  is the state just after the shock.

## 5.2. Derivation of resilience metrics

Return time  $T_r$  :

Set  $F(T_r) = F_0$ :

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<sup>1</sup> The Dirac delta function  $\delta(t - t_i)$  represents an idealized instantaneous shock occurring at time  $t_i$ . It is not a function in the traditional sense but rather a "generalized function" or distribution. Its key properties include (1) being zero everywhere except at  $t = t_i$ , and (2) integrating to 1 over all time, such that  $\int_{-\infty}^{\infty} \delta(t - t_i) dt = 1$ . In this context, it models a discrete shock of magnitude  $M_i$  applied at  $t_i$  by scaling the delta function to  $M_i \delta(t - t_i)$ . For a system, this means that  $F(t)$  is altered instantaneously by  $M_i$  at  $t_i$ , enabling precise representation of sudden disruptions. Readers interested in further mathematical details can refer to Bracewell's foundational work on signal processing (Bracewell 2000).

$$(10) \quad F_0 = F_0 + (F(t_s^-) - F_0 - S_0)e^{-k(T_r-t_s)}$$

Simplifying, we get:

$$(11) \quad 0 = (F(t_s^-) - F_0 - S_0)e^{-k(T_r-t_s)}$$

Since  $e^{-k(T_r-t_s)} \neq 0$

$$(12) \quad F(t_s^-) - F_0 - S_0 = 0$$

So,  $T_r$  can be found as:

$$(13) \quad T_r = t_s + \frac{1}{k} \left| \ln \left( \frac{|F(t_s^-) - F_0|}{S_0} \right) \right|$$

Magnitude of deviation  $D_{max}$ :

$$(14) \quad D_{max} = |F(t_s^+) - F_0| = |F(t_s^-) - F_0 - S_0|$$

Recovery rate:

$$(15) \quad R_t(t) = k|F(t) - F_0| = k|F(t_s^-) - F_0 - S_0|e^{-k(t-t_s)}$$

Equations 1–15 are derived specifically for this study, but they draw from established mathematical principles and prior work in dynamic systems modeling. These equations are grounded in standard differential equations used for analyzing shock-response dynamics and recovery, as seen in studies by Bracewell (2000) and Daley and Vere-Jones (2008). However, the specific implementation of these equations, tailored for food system resilience metrics such as return time, magnitude of deviation, and recovery rate, has not been directly published before. This represents a novel application of these principles within the context of food security. For instance, Equation 5, describing the recovery function  $R(F(t)) = -k(F(t) - F_0)$ , is a standard linear recovery formulation often used in systems governed by exponential decay. While similar formulations appear in prior works on ecological resilience and engineering dynamics (see Carpenter et al., 2001; Holling, 1973), their specific adaptation to food security metrics and integration with stochastic shocks (Equations 6–15) are unique to this study.

### 5.3. Data and model results

To empirically estimate the above derived metrics, we use food prices (as proxy for food security) data from the FAO.<sup>2</sup> Figure 1 shows the trends of the price indices for food, meat, and cereals over time.

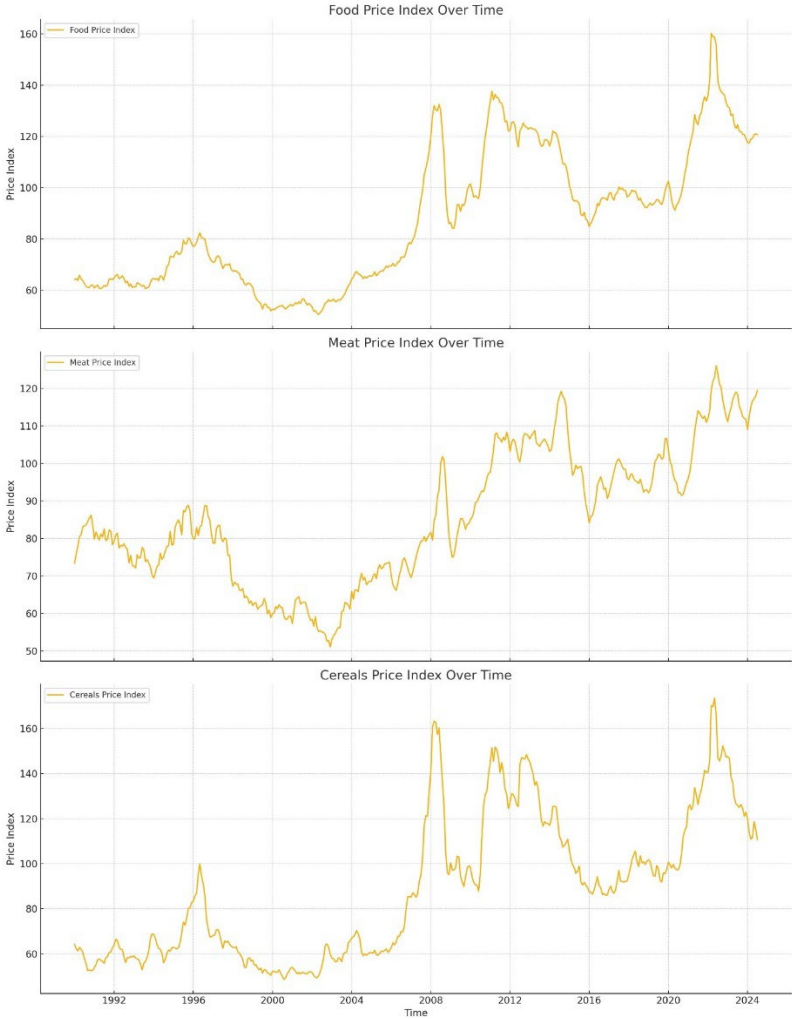
The Food Price Index, as depicted in Figure 1, serves as a composite measure reflecting the aggregate trends of key food commodities, including cereals, meat, dairy, oils, and sugar. Over the observed period, the index exhibits marked fluctuations corresponding to major global

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<sup>2</sup> [www.fao.org/worldfoodsituation/foodpricesindex/en/](http://www.fao.org/worldfoodsituation/foodpricesindex/en/)

events, such as the food price crises of 2007–2008 and 2010–2011 and the COVID-19 pandemic in 2020–2022. These peaks highlight the volatility inherent in global food markets, driven by shocks such as climate disruptions, geopolitical tensions, and supply chain constraints. Despite periods of stabilization, the food price index underscores the interconnectedness of global food systems and the challenges of achieving sustained affordability and accessibility. Its trends provide critical insights into systemic resilience and vulnerability, forming the basis for targeted policy interventions aimed at mitigating price volatility and ensuring long-term food security.

**Figure 1: Food price trends**



**Source:** FAO (2024).

Similarly, the Meat Price Index has exhibited significant volatility, with periodic spikes that highlight the sector’s sensitivity to various shocks. Factors such as disease outbreaks, changes in feed costs, and shifts in consumer demand have all contributed to the sharp increases and decreases observed in the index. These fluctuations reflect the complex dynamics of the meat market, where both supply and demand are influenced by a range of factors, including economic conditions, trade policies, and environmental challenges.

The Cereals Price Index mirrors the trends seen in the broader Food Price Index, with notable spikes during the same periods of 2007–2008 and 2010–2011. These sharp increases were largely driven by supply constraints, including poor harvests and export restrictions by key producing countries. In more recent years, the Cereals Price Index has shown an increasing trend, albeit with significant variability. This trend indicates the ongoing pressures on the global cereals market, where factors such as climate change, population growth, and economic disruptions continue to play a critical role.

Overall, these indices highlight the inherent volatility in global food prices and the challenges posed by external shocks. The patterns observed in recent years, particularly in the wake of the COVID-19 pandemic and ongoing geopolitical tensions, emphasize the need for robust and resilient food systems that can withstand and adapt to these disruptions. As the world faces increasing uncertainties, understanding and addressing the factors driving food price volatility will be crucial in ensuring food security and stability in the years to come.

Table 1 presents key model parameters that define how different food categories—food, meat, and cereals—respond to shocks. These parameters include  $F_0$  (equilibrium state),  $S_0$  (shock magnitude), and  $\delta$  (standard deviation of shocks).

#### *Average value of $F_0$*

The equilibrium state,  $F_0$ , represents the average level around which the price index fluctuates under normal conditions. It serves as a baseline, reflecting the “normal” or expected state of each food category in the absence of shocks.

- **Food:** The equilibrium state for food is approximately 87.45. This suggests that the food price index typically stabilizes around this level, making it a critical reference point for assessing deviations due to shocks.
- **Meat:** With an equilibrium state of 85.65, meat prices tend to be slightly lower than those of food, indicating a relatively stable market that fluctuates around this lower baseline.
- **Cereals:** The cereals category has a slightly higher equilibrium state of 88.83. This baseline reflects the higher average price levels in the cereals market compared to meat and food.

#### *Average value of $S_0$*

The shock magnitude,  $S_0$ , quantifies the average impact size of shocks on the price index. It represents the typical deviation from the equilibrium state caused by external disturbances.

- **Food:** The average shock magnitude for food is 19.81, indicating that food prices are highly sensitive to shocks. This suggests that external disturbances can cause substantial disruptions in the food market, leading to significant deviations from the equilibrium state.
- **Meat:** With a  $S_0$  of 10.08, the meat market exhibits lower sensitivity to shocks. The smaller deviations indicate that meat prices are less affected by external disturbances, reflecting a more resilient market.

- **Cereals:** The cereals category has the highest average shock magnitude of 28.67. This indicates that cereals are particularly vulnerable to external shocks, experiencing the largest deviations from their equilibrium state.

*Average value of  $\delta$*

The standard deviation of shocks,  $\delta$ , reflects the variability in the size of shocks affecting each food category. It measures the unpredictability of shock impacts, with a higher  $\delta$  indicating greater variability.

- **Food:** The standard deviation of shocks for food is 5.51, reflecting moderate variability. While the food market is sensitive to shocks, these shocks tend to be somewhat predictable in their magnitude.
- **Meat:** With a  $\delta$  of 2.21, the meat market exhibits lower variability and greater predictability in the size of shocks. This stability further reinforces the resilience of the meat market.
- **Cereals:** The cereals category has the highest variability, with a  $\delta$  of 8.53. This indicates that shocks in the cereals market are not only severe but also highly unpredictable, making this category particularly volatile.

**Table 1: Model parameters**

Category	Average $F_0$ (equilibrium state)	Average $S_0$ (shock magnitude)	$\delta$ (Standard deviation of shocks)
Food	87.45	19.81	5.51
Meat	85.65	10.08	2.21
Cereals	88.83	28.67	8.53

**Source:** Author.

## 6. Assessing resilience

To assess resilience (see Table 2), we use the 2008 global food crisis as an example. The foundations of the 2008 food crisis were laid as early as 2006, when rising oil prices began to increase the cost of agricultural inputs such as fertilizers and transportation (Headey & Fan, 2008). Simultaneously, growing interest in biofuels, particularly ethanol derived from corn in the United States, diverted vast quantities of crops from food supply chains into energy production (Mitchell, 2008). These shifts in resource allocation occurred alongside unfavorable weather patterns, including prolonged droughts in key grain-producing regions like Australia (FAO, 2008). By 2007, the global supply of staple crops such as wheat, rice, and maize had been significantly strained, setting the stage for what would become a full-blown crisis.

In late 2007, global food prices began to rise sharply, with wheat leading the way due to poor harvests. By early 2008, the crisis intensified. Wheat prices hit record highs in January, followed closely by similar surges in rice and maize prices. Export restrictions imposed by countries like India and Vietnam further exacerbated the situation, particularly in low-income nations heavily reliant on imported food (FAO, 2008).

**Table 2: Results summary**

	$F(t_s^-)$	$k$	$T_r$	$D_{\max}$	$R_t(t)^3$
Food	114.40	0.03	11.18	7.08	0.18
Meat	81.00	0.03	26.59	14.75	0.38
Cereals	132.20	0.03	14.85	14.76	0.38

**Source:** Author's

It is important to note that the thresholds applied in this analysis, such as 10 percent and 20 percent, are entirely arbitrary and are used solely for illustrative purposes to showcase the application of resilience metrics. The selection of thresholds should be context specific, reflecting the unique characteristics and resilience strategies associated with each indicator. For instance, while cereals may warrant tighter thresholds because of established storage and distribution networks, meat production systems might require more lenient thresholds to accommodate longer production cycles and resource dependencies. Similarly, thresholds for food price indices should consider economic conditions and regional market dynamics. This flexibility underscores the importance of tailoring resilience assessments to the specific attributes and challenges of each food system indicator.

Establishing boundaries for each resilience metric helps to define whether or not the system is resilient. These boundaries can be based on historical data, expert opinions, and theoretical thresholds. We use the following boundaries:

#### *Magnitude of deviation*

- Resilient: Magnitude of deviation is less than or equal to 10 percent of the equilibrium state ( $F_0$ ).
- Moderately resilient: Magnitude of deviation is between 10 and 20 percent of the equilibrium state.
- Non-resilient: Magnitude of deviation is greater than 20 percent of the equilibrium state.

#### *Return time*

- Resilient: Return time is less than or equal to six months.
- Moderately resilient: Return time is between 6 and 12 months.
- Non-resilient: Return time is greater than 12 months.

#### *Recovery rate*

- Resilient: Recovery rate is greater than or equal to 1 (full recovery within one year).
- Moderately resilient: Recovery rate is between 0.5 and 1 (full recovery within two years).
- Non-resilient: Recovery rate is less than 0.5 (takes more than two years for full recovery).

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<sup>3</sup> Average between December 2007 and November 2008.

## *6.1 Food*

The food sector demonstrated limited resilience during the 2008 crisis. The equilibrium price index was 114.40 before the crisis, reflecting its baseline stability under normal conditions. The magnitude of deviation was 7.08, indicating a significant perturbation from equilibrium caused by supply chain disruptions, rising oil prices, and export restrictions. The return time was 11.18 months, categorizing the sector as “moderately resilient” in terms of recovery duration. However, the slow recovery rate of 0.18 placed it in the “non-resilient” category, emphasizing the prolonged impact of the crisis on food prices and availability.

This slow stabilization underscored the sector's vulnerability to systemic shocks. The global interconnectedness of food systems, coupled with reduced global grain reserves and export restrictions imposed by key suppliers like India and Vietnam, exacerbated price volatility during the crisis. These findings align with observations from the FAO, which noted that price spikes during the crisis disproportionately impacted low-income and food-importing countries.

To enhance resilience, measures such as investing in strategic food reserves, improving supply chain efficiency, and establishing price stabilization mechanisms are critical. Policies should also address structural vulnerabilities, such as reducing dependency on imported grains and diversifying food production systems.

## *6.2 Meat*

The meat sector displayed relatively higher resilience compared to food. Its equilibrium price index was 81.00, and the magnitude of deviation was 14.75. Despite these significant disruptions, the sector's return time of 26.59 months highlights the longer duration needed for recovery. Notably, the recovery rate of 0.38 positioned it as “moderately resilient” in terms of stabilization speed.

Several factors contributed to the meat sector's resilience. Unlike staple grains, meat production systems tend to be less directly influenced by short-term climatic shocks. However, the sector's reliance on feed inputs—often derived from cereal grains—made it indirectly vulnerable to rising feed costs during the crisis. Disease outbreaks and trade restrictions also compounded challenges, yet the sector's ability to recover reflects robust adaptive mechanisms such as diversified production systems and stronger veterinary services.

To further enhance resilience, targeted interventions should focus on reducing dependency on imported feedstocks, promoting sustainable livestock farming practices, and improving disease surveillance systems. Supporting smallholder livestock farmers with access to affordable veterinary care and financial services could also bolster the sector's stability during future crises.

## *6.3 Cereals*

The cereals sector faced pronounced disruptions during the 2008 crisis, with an equilibrium price index of 132.20 and a significant magnitude of deviation of 14.76. The return time was 14.85 months, indicating a moderate duration for recovery. The recovery rate, of 0.38 categorized cereals as “moderately resilient,” reflecting variability in the sector's ability to stabilize following shocks. The cereals market was particularly susceptible to the cascading effects of

climate change, export bans, and increased demand for biofuel crops like maize. For instance, droughts in Australia and poor harvests in other key grain-producing regions significantly reduced global supply. Export bans imposed by major producers, such as Russia and Ukraine, further constrained availability, leading to sharp price spikes.

Strengthening resilience in the cereals sector requires a multifaceted approach. Investments in drought-resistant crop varieties, improved irrigation systems, and robust storage infrastructure are essential. Enhancing international cooperation to prevent export restrictions during crises could also mitigate future disruptions. Policies promoting sustainable agricultural practices, such as crop rotation and reduced reliance on chemical inputs, can further stabilize production systems and ensure long-term resilience.

The distinct resilience metrics for food, meat, and cereals underscore the necessity for tailored policy approaches. For the overall food sector, where significant variability and slow recovery are prevalent, policies should focus on establishing strategic reserves, enhancing supply chain infrastructure, and implementing market stabilization mechanisms to manage severe shocks. In the meat sector, where resilience is higher, efforts should concentrate on maintaining and enhancing existing strengths, such as improving veterinary services and promoting technological innovation in livestock farming. For cereals, where recovery is moderate and deviations are notable, policies should prioritize the development of drought-resistant crop varieties, improved irrigation, and better postharvest management practices.

## **7. Concluding remarks**

In the context of increasing global shocks and stresses, it is imperative to have reliable, nuanced, and dynamic metrics for assessing resilience, particularly in food systems. This paper has examined several popular resilience metrics, such as the FSNRI, the RCI, and the RIMA, alongside others like the HDDS and the LRI. While each of these metrics provides valuable insights into food system performance, they fall short in capturing the full spectrum of resilience, particularly the attributes of return time, magnitude of deviation, and recovery rate. These three attributes are critical for developing a comprehensive understanding of how food systems withstand shocks and recover and for guiding effective policy interventions.

The concept of return time—the period it takes for a system to recover and return to its pre-shock equilibrium—is largely overlooked in existing metrics. Most metrics provide static snapshots of resilience, capturing a system's state at a particular point in time without considering how long it takes for systems to stabilize. Yet, the ability of a food system to quickly return to equilibrium after a disturbance is crucial for mitigating the long-term effects of shocks, such as those caused by climate change or economic crises. Without accounting for return time, policymakers may implement interventions that focus on temporary solutions rather than addressing systemic vulnerabilities that delay recovery.

Similarly, the magnitude of deviation—the extent to which a system is pushed away from its equilibrium state by a shock—is inadequately addressed in current resilience assessments. Understanding the depth and severity of disruptions is vital for assessing the true impact of shocks on food systems and for designing interventions that address both immediate needs and long-term stability. Metrics that do not consider magnitude of deviation may fail to capture the

full range of vulnerabilities, especially in low-income regions where shocks can lead to significant disruptions in food availability, access, and utilization.

Finally, recovery rate—the speed at which a system returns to its normal functioning—remains undermeasured across most existing metrics. The recovery rate is a dynamic aspect of resilience that determines how quickly a system can regain stability after a shock, making it critical for preventing protracted periods of food insecurity. Metrics that fail to incorporate recovery rate are likely to overlook the effectiveness of resilience-building measures, such as social safety nets or infrastructural investments. Consequently, interventions based on incomplete assessments may lead to cyclical crises, where vulnerabilities persist and shocks continue to undermine food security.

Incorporating these three resilience attributes into a cohesive and comprehensive resilience assessment framework, as proposed in this paper, provides a more accurate and actionable understanding of how food systems respond to and recover from shocks. The framework enhances the ability of policymakers to design targeted interventions that address sector-specific vulnerabilities. For example, cereal production systems, which exhibit higher variability and slower recovery rates, would benefit from policies promoting drought-resistant crops and improved irrigation infrastructure. Meanwhile, the relatively resilient meat sector could focus on sustaining its high recovery rates through technological innovation and enhanced disease management programs.

Moreover, this integrated framework moves beyond traditional resilience assessments, which often prioritize singular metrics and static measures. It advocates for a dynamic and multidimensional approach that recognizes the complexity of food systems and the diverse factors influencing their resilience. By integrating return time, magnitude of deviation, and recovery rate, the framework ensures that resilience assessments are not only more holistic but also better suited to inform sustainable and adaptive policy interventions.

In conclusion, the shortcomings of existing resilience metrics in capturing return time, magnitude of deviation, and recovery rate underscore the need for more comprehensive and dynamic tools to measure food system resilience. This paper's proposed framework addresses these gaps, providing a balanced and tailored approach to resilience measurement that can more effectively guide policy and practice. As the frequency and severity of global disruptions continue to rise, the adoption of this framework will be essential for building resilient food systems capable of withstanding future shocks and ensuring food security for all.

As global food systems continue to face unprecedented disruptions, the need for precise, timely, and cost-efficient resilience metrics is critical. While traditional resilience measurement methods are often data intensive and financially prohibitive, satellite imagery and AI-driven analytics present a promising alternative. These technologies allow for dynamic, high-frequency data collection across broad geographic areas, facilitating a more granular understanding of resilience in food systems. Such innovations not only reduce the costs associated with data acquisition but also enable policymakers to make informed, evidence-based decisions that are adaptive to real-time conditions. Embracing satellite and AI technologies in resilience assessments could thus transform food system resilience measurement, making it more accessible, efficient, and impactful.

Future research should focus on refining these resilience metrics and exploring their applicability across different food systems and geographic contexts. There is also a pressing need for the development of adaptive policy frameworks that can dynamically respond to changes in resilience metrics in real time. Longitudinal studies tracking the effectiveness of resilience-building interventions over time will provide valuable insights into how systems adapt and recover. In addition, further work is needed to integrate social and environmental dimensions of resilience, particularly the role of community support networks and ecosystem health in enhancing long-term food security.

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