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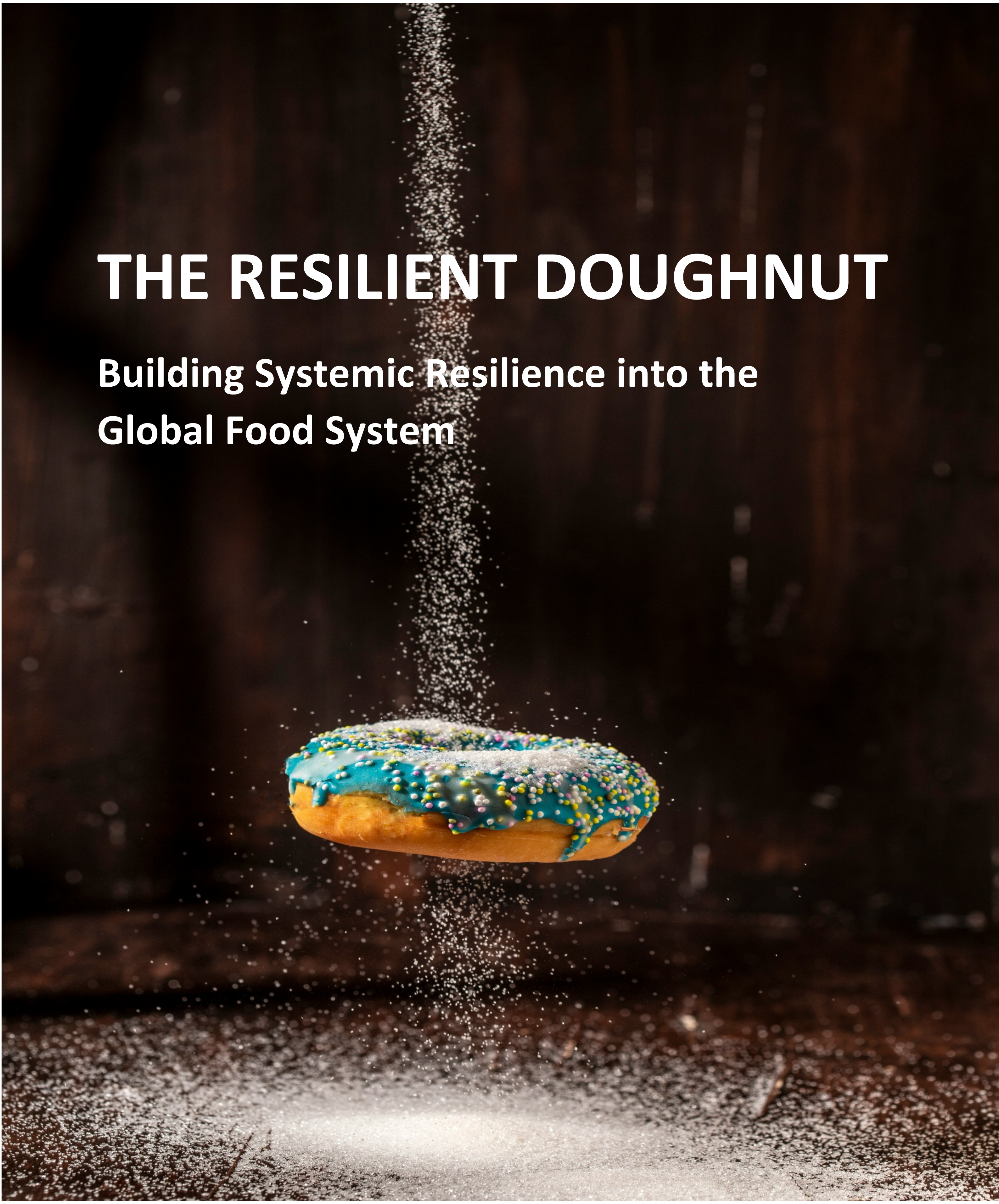
THE RESILIENT DOUGHNUT

Building Systemic Resilience into the Global Food System



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OXFORD MARTIN SYSTEMIC RESILIENCE INITATIVE

The programme aims to contribute to the resilience of states and global systems by identifying and advancing practical solutions for managing systemic shocks with the potential to cause major and prolonged economic disruption. It seeks to uncover how to pinpoint and integrate interventions that can strengthen systems' capacity to resist shocks, prevent contagion, and avoid cascading failures that may lead to catastrophe. The progamme also aims to provide actionable templates for implementing such solutions. Our intended outcome is to motivate and guide action by key decision-makers by offering evidence-based tools and templates, facilitating dialogue, supporting the co-creation of solutions, and building institutional capability.

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ABOUT THE ENVIRONMENTAL CHANGE INSTITUTE

The Environmental Change Institute at the University of Oxford was established in 1991. Its aim is to organise and promote interdisciplinary research on the nature, causes and impact of environmental change and to contribute to the development of management strategies for coping with future environmental change. Our ultimate goal is to contribute to more resilient, adaptive, and sustainable systems at local, national, and global levels.

ACKNOWLEDGEMENTS

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ABBREVIATIONS

Acronyms	Definitions
ABM	Agent-based model
CGE	Computational general equilibrium model
EC	European Commission
EU	European Union
FAO	UN Food and Agriculture Organization
FBS	FAO Food Balance Sheet
FOLU	Food and Land Use Coalition
IMF	International Monetary Fund
IFAD	UN International Fund for Agricultural Development
ILO	UN International Labour Organization
LMIC	Low- and Middle-Income Countries
NGO	Non-Governmental Organisation
OECD	Organisation for Economic Co-operation and Development
PE	Partial equilibrium model
SDGs	UN Sustainable Development Goals
SJDC	Safe and Just Decision Corridor
UN	United Nations
UNDRR	United Nations Office for Disaster Risk Reduction
UNEP	UN Environment Programme
WB	World Bank
WFP	UN World Food Programme
WHO	World Health Organization
WTO	World Trade Organization

EXECUTIVE SUMMARY

GET INTO THE DOUGHNUT: IMPLEMENTING SYSTEMIC SOLUTIONS AT SCALE

The global food system is arguably one of our most critical systems. It impacts billions of people globally and depends on a complex network of producers, processors, distributors, and consumers. Simultaneously, the global food system in interconnected with other global systems such as trade, energy, and infrastructure; commodities such as oil and chemicals; as well as local climate and water resources. It also encompasses a vast global business network, estimated to contribute around USD 10 trillion to global GDP a year.

Yet **this system – vital to human life and the global economy – faces several overlaying and interconnected threats,** including a growing global population, climate change, biodiversity loss, environmental degradation, economic crises, pests and pandemics, as well as war and conflict. Such shocks can affect several or all sectors of the system, from inputs to production to waste management – with the potential to cause systemic collapse or failure. Indeed, the high degree of interconnectedness among different actors within the food system can lead to cascading effects, in which an initial shock is amplified to cause greater damage. At the same time, as a major driver of environmental degradation and climate change, the food system itself is a significant source of systemic risk.

Moreover, resistance to change of unsustainable activities and norms currently locks in existing inefficiencies and inequalities and erodes long-term functioning of the system. In its current state, the global food system crosses Earth's planetary boundaries in multiple dimensions, and scientists are in broad consensus on the urgent need for food system transformation towards sustainability. **Long-term resilience depends on a transformation to a more sustainable food system.**

By analogy with Kate Raworth's *Doughnut Economics* diagram for a regenerative and distributive economy, **this research refers to the 'Resilient Doughnut' to emphasise the urgent need to shift our food system into the safe and just space** – between meeting the social foundations (defined as the minimum requirements for a thriving human society) and staying within the planetary boundaries. The food system must be capable of remaining within those boundaries when disturbed by shocks – in other words, **it must be able to *get into and stay inside the Doughnut.***

We need to advance resilience across three critical pillars: buffer, adaptive, and transformative capacities. Buffer capacities, such as grain storage, are essential for rapidly absorbing the direct effects of shocks over short periods. Adaptive capacities refer to the internal capacities of the food system to respond to new circumstances – for example, by adjusting supply chains. Transformative capacities, in turn, involve the system's ability to change its behaviour entirely and transform to a new state (e.g. by adopting sustainable agricultural practices). With increasing severity and duration of shocks, the risk of systemic failure grows, while response options diminish. This underscores the importance of food system transformation to achieve a more sustainable and less vulnerable state – while also recognising that short-term buffers and adaptive capacities are needed to absorb inevitable short-term trade-offs.

Analysis of the current state of the food system shows that urgent action is needed to avoid rising future losses (ranging from financial losses to the loss of human lives), with greater shocks expected from ongoing climate change and biodiversity loss. This includes the need to ensure the short-term functioning of the food system on a global scale by keeping trade open, while providing targeted aid to populations most affected by current shortfalls. In addition, agricultural subsidies must be redirected to support sustainable actions, while greater efforts are needed to limit further climate change, biodiversity loss, land and water degradation, and the amplification of existing socioeconomic inequalities.

Most global efforts focus on securing local food security in countries grappling with egregious risks. **While context specific interventions are warranted, strengthening the global food system necessitates consideration of all dimensions of the food system** – including feedback loops, distant connections, and possible trade-offs – to avoid undesirable outcomes. Current reactions to crises often focus solely on food security, agricultural productivity, and local scales. Such narrow strategies can endanger the functioning of the food system by directly triggering cascading losses (e.g. through export bans) or fuelling long-term degradation (e.g. driving further land use change or aiming at a return to a previously unsustainable state). To avoid jeopardising future resilience, interventions should consider all outcomes (economic, social, environmental, and food security), as well as all spatial and temporal scales.

As such, **building systemic resilience in the food system requires an understanding of global dependencies, holistically designed interventions that reach all levels, and the inclusion of stakeholders from all sectors of the system.** This can be achieved only through coordinated global action. Yet no single international organisation is responsible for measuring and stewarding the resilience of the food system as a whole. Instead, a patchwork of public and private entities operates at different levels, driven by different incentives and objectives. We argue that this **governance gap constitutes a major hurdle to the achievement of long-term sustainability and resilience in our food systems**. New global level coordination and action must be ignited to effectively address the existing systemic risks to the global food system.

KICKSTARTING A REVOLUTION IN RISK MONITORING

Monitoring is the foundation for effective governance and policy solutions. To build systemic resilience within the global food system, monitoring its current state – as well as the underlying dynamics, drivers, and critical vulnerabilities – is essential. What gets measured gets managed; conversely, blind spots typically translate into inaction. Monitoring systems must be scientifically rigorous, multidisciplinary and inclusive to enable a systems perspective that reflects the multidimensional and multi-scaled nature of the food system. Tracking change, identifying entry points for interventions and possible trade-offs, as well as developing a true cost accounting approach – including the costs of unsustainable environmental or social outcomes – are paramount to identifying priorities, setting common targets among stakeholders (including monitoring and accountability), and implementing effective policy interventions.

Whether a shock causes a systemic risk to the global food system depends as much on the underlying structural properties, current stress levels, and resilience capacities of the food system as on the properties of the shock itself. Therefore, **threats, stress levels, and resilience capacities have to be quantified and measured over time to estimate risk and identify opportunities for positive change**. At the same time, the multi-scaled nature of resilience and the complexity of the food system challenge the identification of optimal interventions through predictive modelling. Hence, approaches to implementing resilience should be flexible and regularly monitored to avoid undesirable outcomes, track progress, and enable adaptation to changing circumstances. To date, no framework exists to measure the success of interventions aimed at building systemic resilience. As such, there is an **urgent need to develop monitoring and evaluation approaches that capture the effectiveness of implemented solutions**.

More research linking the desired and actual outcomes of policies is needed to enable effective monitoring, impact evaluations, and policy learning. Interdisciplinary work must consider the social, cultural, and political context of individual interventions, as well as the availability of transformative capacities to implement changes in an equitable and lasting manner.

OVERCOMING CRITICAL INFORMATION GAPS

Modelling is a powerful tool to estimate the effectiveness of interventions and quantify changing risks under different future scenarios. However, modelling relies on the existence and availability of reliable data on all food system activities (not just agriculture), with global coverage. Analytical tools and methods from network theory, climate science, and statistical analysis should be deployed to capture the effects of cascading and compounding risks (situations in which several risks or their impacts overlap or co-occur), such as multiple breadbasket failures. This requires a redoubling of efforts for interdisciplinary collaboration and overcoming key data gaps, especially beyond production shocks.

Expanding the geographical coverage of key resilience indicators is essential. International institutions (e.g. FAO, WB, or WHO) that collect data on the food system and associated outcomes offer different spatial coverage, and indicators are often only available for specific subsets of countries. This not only restricts comparisons between countries for each indicator but also hinders the calculation of compound metrics and the simultaneous monitoring of different dimensions globally. Moreover, current food systems indicators are tailored towards food security and agricultural production. However, in an interconnected global food system pre-farmgate inputs, trade, post-farmgate processing, and distribution of goods are entry points for systemic risks. As such**, pre- and post-farmgate indicators and emerging properties have to be quantified** to capture the full system and to develop early warning systems for disruptions (e.g. data on the dependency of value chains on certain trade chokepoints).

1. INTRODUCTION: CURRENT CHALLENGES TO THE FOOD SYSTEM AND THE NEED FOR TRANSFORMATION

The global food system has faced multiple severe shocks in recent years (5) (e.g. the 2007–2008 crises, driven by major droughts and further impacted by the financial crises (3), the impacts of the COVID-19 pandemic, and Russia's invasion of Ukraine). (4) These shocks have revealed the existing vulnerabilities within the global food system, which is susceptible to partial and systemic failure and cascading effects. With disaster frequency rising significantly in the new millennium (5), the probability of future shocks continues to increase, driven by ongoing climate change, biodiversity loss, and the high risk of cascading losses caused by high levels of interconnectedness and specialisation. (6–10) Excessive loss and damage, including deaths, increased poverty and frequency of economic crises are inevitable if the food system does not transform and reach a more sustainable and resilient state, preventing it from total failure.

THE CURRENT CRISIS

Russia's ongoing war in Ukraine, as well as the remaining effects of the global COVID-19 pandemic, paired with poor harvests in South America in 2021 and 2022, have dramatically highlighted the vulnerability of our increasingly globalised food system. (11–13)

Affecting two countries in a major breadbasket region responsible for, inter alia, the production of wheat, maize, barley, and sunflower oil, and representing 12% of the global market share of calories (12), the Russia–Ukraine war has yielded several direct and indirect consequences for the global food system. (11) The direct effects of the war have included shortfalls in agricultural production in Ukraine and a decline in exports of food and fertiliser produced in the country. The consequent drastic increases in fertiliser and food prices have triggered cascading effects, including production declines in countries depended on these supplies (fertiliser and ingredients). This has given rise to protectionism (export bans) and caused panic buying, currency depreciation in food-importing countries, and commodity speculation. (11, 12) Simultaneously, other parallel events – including droughts and floods in other major global food producing regions (e.g. South America) – have added further stress to the global food system. (14)

The resulting food crisis has disproportionately affected the world's poorest populations, particularly those in Sub-Saharan Africa. (11–13,15) A 2022 United Nations World Food Programme (WFP) report on the consequences of the Ukraine war identifies a rise of about 200 million people acutely affected by or at high risk of food insecurity, 'driven by ripple effects of the conflict.' (16) Additionally, the current food crisis has significant economic impacts on countries through increased import bills (due to higher food and fertiliser prices), fiscal measures aimed at mitigating the effects of higher food prices cutting into national budgets, and the direct costs of food aid for populations facing acute food insecurity. (15)

A CALL FOR TRANSFORMATION

The current crisis amplifies pre-existing trends in the food system. In the 2020s, progress in fighting malnutrition has come to a halt (8) and the double burden of disease (defined as the simultaneous occurrence of hunger and obesity) is driving up the pressure on healthcare systems in many countries through increases in non-communicable diseases – the number one cause of death globally. (1, 17)

The global food system embeds deeply interconnected supply chains and trade systems, being thereby prone to cascading shocks. Indeed, disruption to trade has emerged as a major concern for countries heavily relying on imports or exports of certain goods. (7, 8, 18) Multiple interwoven challenges – such as climate change, conflict, dietary shifts, population growth and economic crises – and consequently increased risks of systemic failure of the food system are driving the need for its transformation. (6–8, 19) Simultaneously, being primarily optimised for production efficiency, the food system is one of the main drivers of global terrestrial biodiversity loss, habitat and soil degradation, greenhouse gas emissions, freshwater withdrawal, and pollution (7, 8, 20–22), crossing several of Earth's planetary boundaries. (23) At the same time, the system is flawed with persistent inefficiencies resulting in high inequality in food distribution and one-third of global production being lost or wasted. (20) In addition, food crises do not only lead to food insecurity, hunger, malnutrition, and death but have the potential to further amplify social crises causing unrest, conflict, and large-scale migration. (15) These shortfalls and pivotal risks to human and planetary life warrant a profound transformation in our global food system.

The Food and Land Use Coalition (FOLU) has identified critical transitions needed for a more sustainable, resilient global food system. These include 1) direct adaptations of the food chain, such as reducing food loss and waste or building local loops and linkages, 2) social changes, including a dietary shift and harnessing the digital revolution, and 3) ecological changes, such as protecting and restoring nature and working towards a healthy ocean. (1) Yet, many have called out the current inaction, with the authors of the above-mentioned WFP report stressing the 'very real risk that global food and nutrition needs across the globe may soon outstrip […] any organization's ability to respond.' (16)

Furthermore, lessons from past food crises show that current responses to shocks are often not only insufficient, but exacerbate negative effects even further (e.g. by imposing export bans on domestic production or engaging in panic buying causing further price increases and insufficiency of supply). (12) This highlights the need for international governance to shift from a localised or national view of food security to a global systems perspective and action, which accounts for the emergent outcomes of high interconnectedness and its multi-scalar and multi-dimensional nature to prevent future damage and a total collapse.

Our global food system remains far from fitting inside the safe Doughnut space. It falls short in providing healthy and nutritious food for all (while providing secure and fair livelihoods and supporting equity and social justice) and respecting Earth's Planetary Boundaries (not causing further damages to our climate and the biosphere). (2) **Now is the time to act: our collective response to the current crisis must catalyse a shift toward long-term resilience and sustainability in the food system.**

REPORT OUTLINE

This report reviews the current state of research on systemic risks and systemic resilience within the food system and provides initial insights to guide the next steps in building systemic resilience. In so doing, we draw on Raworth's 2017 framework of *Doughnut Economics* to illustrate the need for a system-wide transformation and to highlight the role of sustainability as a prerequisite for systemic resilience in the global food system.

The report begins by presenting (in Section 2) the conceptual background needed to quantify and understand systemic risks and systemic resilience within the food system, and it clarifies the terminology adopted throughout. Section 3 discusses the threats and stressors to the food system. Section 4 reviews existing approaches to risk quantification and considers which types of indicators are required to effectively assess sustainability and resilience, while also highlighting key gaps in data availability. Modelling approaches for assessing systemic risk and resilience are introduced in Section 5. Finally, Section 6 presents theoretical considerations for effective policy interventions to drive food system resilience and summarises those proposed in the literature. Additionally, lessons learned from past food crises are reflected upon to highlight counterproductive responses that may hinder, rather than build, resilience.

2. FOOD SYSTEM – SYSTEMIC RISK AND RESILIENCE

This section conceptualises the global food system and introduces the terms 'systemic risk' and 'systemic resilience', both with a general view across disciplines and more specifically in the context of the food system. Additionally, the chapter sheds light on the different positions held by international organisations on systemic resilience of the food system. The section closes with a suggested definition of systemic resilience within the global food system, adopted throughout this report.

THE FOOD SYSTEM – A SYSTEMS PERSPECTIVE

The global food system contains multiple sub-systems, that can be modern (organised by large international companies relying on complex food chains), traditional (based on subsistence farmers and local markets and supply chains), or a mix of the two. (8) As social-ecological systems, food systems cover social, economic, political, institutional, and environmental dimensions and are embedded in their natural, as well as human environment, as illustrated in Figure 1 below. (7, 19)

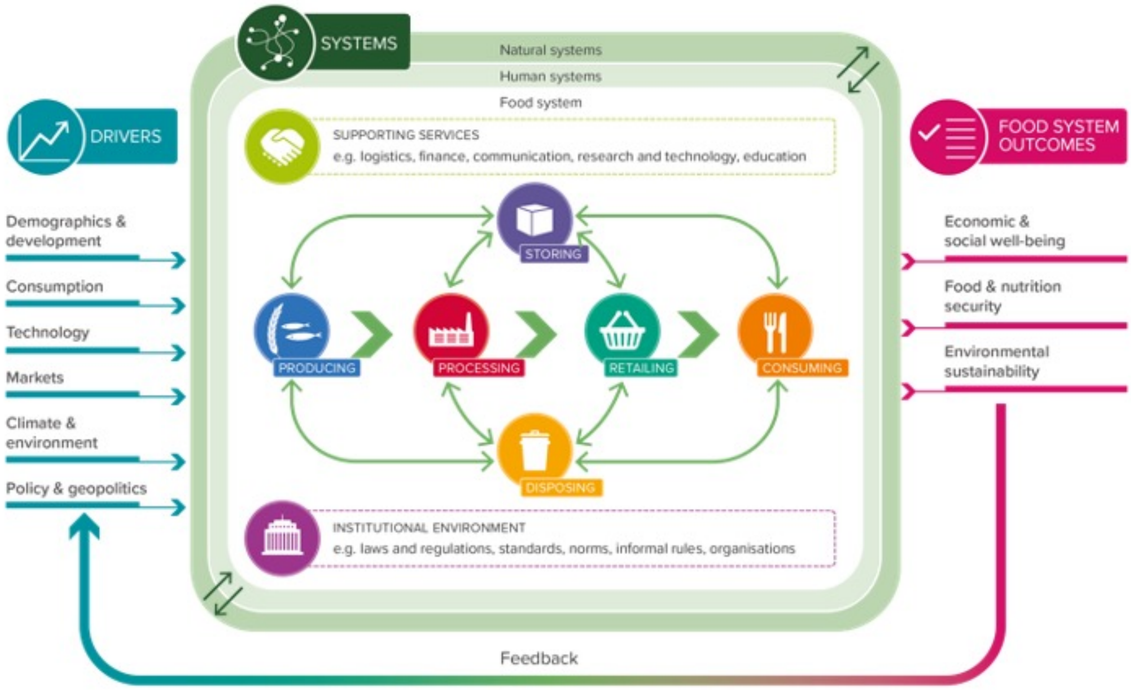

Figure 1: The food system is a complex system and comprises all activities related to food producing, processing, retailing, storing, consuming and disposing, carried out by different food system actors. These activities lead to food system outcomes that include economic and social wellbeing, food and nutrition security as well as environmental impacts. Socio-economic and natural developments (drivers) influence the actions of these actors, which might themselves be impacted by the food system. The food system is embedded in the natural and human system, which provide the foundation for the food system's functioning. (Diagram is made available through Foresight4Food).

Food systems comprise all activities related to the production, processing, packaging, storing, retailing, distributing, consuming and disposing of food. (7, 8, 19) Interactions within the food system are realised by food system actors – which can be people, companies and institutions – influenced by the institutional environment (made of laws and governance structures, norms, informal rules and organisations), as well as supporting services (for example logistics or technology) (7) in their respective contexts. Outcomes of the food system are not limited to food and nutrition but relate more broadly to the economy and social well-being, e.g. livelihoods depend on different aspects of the food system. The global food system's outcomes are equally pertinent for environmental sustainability, and its nature-positive functions can include safeguarding and restoring ecosystem health and contributing to climate mitigation and adaptation (see Figure 1). (7, 24, 25)

Term	Explanation
Actors	Actors comprise all individuals or entities that engage in different food system sectors. They can be people, companies and institutions (e.g. governments, regulatory agencies).
Dimensions	Dimensions refer to the different areas in which food system outcomes can be measured, including food and nutrition (including food security and health), economic impact, social wellbeing, and environmental impacts.
Drivers	Drivers are external forces that impact actors' activities within the food system. Drivers might be directly influenced by food system outcomes.
Outcomes	Outcomes are all ways in which activities within the food system are influencing itself or the non-food environment.
Scales	Geographical or structural scales of the system and subsystems. Geographical scales refer to the spatial extend of the system considered and can range from local to global. Structural scales refer to the level of organisation, ranging from the individual to multi-national companies and international trade systems.
Sectors	Sectors refer to the different clusters of activities within the food system. They comprise production, processing, packaging, storing, retailing, distributing, consuming and disposing of food.

Table 1: Terminology adopted in this report.

Activities within the food system are based on the relationships and interactions of food system actors, who are impacted by external *drivers* (see Figure 1). These drivers, themselves influenced by the outcomes of the food systems, are related to all *dimensions* of the food system, including social drivers (e.g. demographics and development), environmental drivers (e.g. climate and biodiversity), as well as economic drivers (e.g. markets and consumption preferences). Moreover, the food system operates on and includes different geographical and structural scales, from individuals, such as farmers or consumers, to multi-national companies and international trade systems. Feedback loops, interlinkages between scales and possible trade-offs require consideration of all dimensions and scales of the food system to enable an understanding of systemic risk and resilience. (7, 19, 26, 27)

Furthermore, Sillmann, et al. (2022) (27) identify three interacting spheres which must be addressed in parallel to enable transformations within the system. These include the *political sphere*, which manages risks at a societal level, and the *personal sphere*, which contains individual attitudes and actions. However, outcomes are measured in the *practical sphere*, which covers technical responses, such as knowledge, innovation, management and changing behaviour. Incorporation and recognition of all three spheres is important to enable a successful transformation towards a more resilient system.

SYSTEMIC RISK – CONCEPT AND IMPLICATIONS FOR SYSTEMIC RESILIENCE

A complex system, such as the food system, is more than just a sum of its parts — it 'exhibit[s] emergent properties that arise from interactions among its constituent parts.' (28) Those properties cannot be explained through analysis of individual actors, subsections or on specific spatial scales, but result from network effects and interactions within the panarchy of the system, which has important consequences for the occurrence of systemic risks.

Systemic risks are broadly understood as the 'risk of a generalised failure or collapse of all the components of a system.' (29) However, the specific definitions and underlying conceptual understandings of systemic risk vary across disciplines. Based on the assumption that systemic risks are too complex to be captured by conventional risk calculations, some hold a purely ontological perspective that merely acknowledges the existence of systemic risks but makes no attempt to analyse or quantify such. (30) This notion of immeasurability is sometimes set apart from the term risk and instead transferred to the associated uncertainty, by defining risk as the 'portion of the unexpected that can be quantified by the calculation of probabilities.' (28) The notion of quantifiable systemic risk relates to an epistemological perspective which contrasts the ontological perspective and assumes that knowledge about systemic risks can be acquired. Two different underlying epistemological positions have emerged. *Analytical realism* assumes systemic risks to be real threats and considers that their risks and consequences can be calculated with some level of reliability. In contrast, epistemic *analytical constructivism* draws on systems theories, such as complex systems theory or dynamic network theory, to identify emergent features and main characteristics of highly complex and dynamic risks. However, prediction or empirical validation is assumed to be impossible due to the high complexity, interconnectivity, and non-linear relationships. (30)

Indeed, most definitions of systemic risk imply such risks to include a certain level of underestimation, uncertainty and unpredictability. What makes risks *systemic* is cascading effects – huge damage and negative effects reaching large parts of the system at once or gradually. (27, 30) Summarising different sectorial and disciplinary perspectives, Renn, et al. (2020) identify four major properties of systemic risks, including:

1) complexity (difficult to identify and quantify),

2) uncertainty (limiting estimates of cause-effect chains),

3) ambiguity (resulting from interpretation differences of factual statements or applying normative rules), and

4) causing cascading effects.

These properties explain the underestimation and unpredictability of systemic risks. The authors go on to list four attributes related to the causal structure and dynamics of systemic risks, which further increase the difficulty of quantification and prediction:

1) transboundary and cross-sectional impacts (potentially leading to multiple cascading effects);

2) high interconnectedness between risks (resulting in complex causal relationships, high uncertainty, and interpretative ambiguities);

3) nonlinear cause-effect relationships with possible tipping points[a]; and

4) increased uncertainty due to the stochastic nature of the relationship between cause and effects which hinders characterisation with statistical confidence intervals. (30)

Non-linearity and uncertainty make it especially hard to quantify systemic risks effectively.

Furthermore, shocks, with the potential to cause a systemic risk, vary greatly and can be non-exclusively physical, biological, environmental, technological, social, political or even psychological (e.g. food safety scares). They might be sequential, synchronous, or simultaneous, and can include or lead to cascading effects and the crossing of tipping points.(31) Scholarship on finance theory expounds on different types of shocks and the nature of their impacts on systems. This literature highlights that exogenous events that disturb all or most actors within the system simultaneously represent an aggregate shock from the outset and are sometimes called ‘hurricane’ or ‘polysynchronous’ events. One such example is the internal oscillation of the climate cross-correlated with peak discharges in rivers in Central and Eastern Europe affecting multiple ports and trade routes simultaneously. This type of shock is closely related to long-term causes of events, which are not tracked or managed but have a latent or cumulative risk potential to appear suddenly when some characteristics of the system change. ‘Domino effects’, in contrast, can be caused by exogenous or endogenous, localised events that cascade into all or most parts of the system through interlinkages and feedback loops. Systemic risks associated with such events are sometimes referred to as ‘femtorisks’ – a term that closely focuses on the short-term process of disruption. (28, 29)

[a] A tipping point refers to the crossing of a threshold, which leads the system into a new state, potentially associated with irreversible changes (e.g. collapse of an ecosystem). (36, 87)

Box 1. Definition of Systemic Risk to the Global Food System

This report focuses on the notion of extensive damage reaching several or all parts of the system when considering systemic risks to the global food system. Systemic risks are thus understood as the tail risks of the damage distribution (extreme damage above a certain threshold, see **Error! Reference source not found.**), causing a **serious failure or collapse of one or several main outcomes** of the system, which might cascade into other systems not primarily associated with food, for example affecting the global economy or the financial market. This technical definition is adopted to emphasise the potentially catastrophic outcomes of systemic risk occurrence, rather than the attributes of a specific risk scenario.

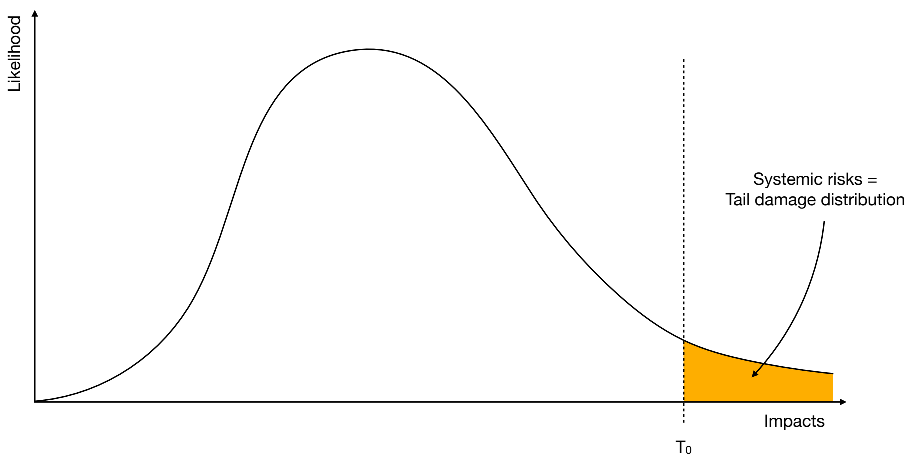

Figure 2: Systemic risk is defined here as the tail risk of the impact distribution, above a certain threshold T0. These risks are low in probability but have very high potential impact. While the exact shape of the damage distribution remains unknown (displayed curve is just for illustration), damage distributions of highly interconnected systems, such as the food system, are often expected to have fat tailed distributions, with increased likelihood of catastrophic failure. (142,152,153)

Given the extant complexities of the global food system illustrated above, it is crucial to move beyond considering distinct risks in a siloed manner. (28) Transdisciplinary and integrated risk assessment and decision-making are needed to design and implement interventions that allow for connected and collective action driving systemic change. Additionally, risk knowledge must include trans-contextual and relational information, and it needs to be made broadly available and communicated in an accessible manner to all relevant stakeholders. (27, 28) Given the dramatic extent of consequences that systemic risks may potentially cause, building resilience might be hindered by a feeling of impracticability and lack of support for the seemingly high costs involved. (30, 32) However, while challenging, building systemic resilience is essential to prevent accumulating costs (social and monetary) of ad-hoc intervention measures over time. (32)

SYSTEMIC RESILIENCE – GENERAL CONCEPTUAL INTERPRETATIONS ACROSS DISCIPLINES

On the flipside of systemic risk, there is *systemic resilience*. The term was first introduced as a highly influential concept in the field of ecology by C.S. Holling in 1973 (33), but has since been used, transferred and adopted in other disciplines, such as biology, psychology, social and cultural sciences, economics, law, and communication. (19, 34, 35) Broadly defined, the resilience of a system can be understood 'as the dynamic capacity to continue to achieve goals despite disturbances and shocks.' (19)

Across fields, systemic resilience is typically characterised by continuous learning and adaptation, and the necessity of trade-offs (either between interacting systems or within the system's panarchy). (34) Open, dynamic complex systems which display resilient behaviour, are expected to promote connectivity between actors, demonstrate experimentation and learning and are associated with high levels of diversity, redundancy, and participation. (34,36) Furthermore, emerging network properties of systems such as interconnectedness and centrality are found to be key to understanding the propagation of cascading effects, which are essential threats to systemic resilience. (9, 13, 37)

Even though scholars agree on the general notion of resilience, broadly summarised by Tendall, et al. (2015) (19), several conceptual disagreements and tensions remain. On the one hand, resilience is understood – as most famously expressed in engineering sciences – as a 'bounce-back' to the pre-disturbance functioning of the system, which is assumed to be a desirable state. On the other, a ecosystems approach perceives resilience as the ability to undergo change in the experience of shocks while maintaining its basic structure and functions. (26) This relates to tensions about the existence of one desirable equilibrium state in which the system should be retained by resilience measures. Especially in the field of economics, the concept of 'equilibrium thinking' assumes that the system only deviates from a desirable equilibrium state in the presence of external shocks. (32) In contrast, the idea of a 'dynamic disequilibrium' (38) suggests that a system evolves towards a critical state in which cascading effects are possible, if not constantly corrected by adaptation and learning. (32)

It is important to note that the conceptual understanding of stability has direct implications on the types of interventions deployed to pursue resilience. The first possible strategy relies on interventions in direct response to disruption, through tailored policies for the most affected parts of the system. This approach might require trade-offs with other systems and prove cost-intensive in the long run should shocks cumulate. The second possible strategy is one of resilience by design. This is based on self-organising and adaptive relationships built ex-ante to risk occurrence. This approach enables positive side effects and synergies, while limiting future losses, but is often associated with higher initial costs. (32)

Another tension arises concerning the question of whether and how resilience can be measured within a complex Social-Economic System (SES). Some scholars interpret resilience mainly as a metaphor for supporting collaboration and adaptive response capacity building. Others take one step further and rely on descriptive analysis, broad indicators and system attributes used as proxies for resilience, while highlighting the impossibility of direct measurement (in line with epistemic analytical constructivism). (29) The opposing view is that resilience concepts are relevant only if empirical assessments or modelling are used to capture and quantify the system. Here scholars quantify the resilience of specific system components to a selection of possible shocks using modelling and simulation. (26)

Given that complex systems like the global food system are multidimensional and multi-scaled (24, 35), the question of how much knowledge can be derived from studying individual (sub-)levels of organisation or system components remains contentious. While some scholars focus on specific parts of the systems (examples for the food system are shared below), others argue that without a 'whole systems' approach, complex system interactions will be misinterpreted or completely omitted (which is the view adopted in this report, as elaborated further below). Regarding SES, further disagreement exists regarding of the extent to which social rights and justice issues should be integrated into the concept of resilience. It has been questioned whether a fundamentally unjust or structurally unsustainable system can be resilient at all, and whether normative positions and 'desirable' outcomes should be defined more clearly to study and implement policy measures in pursuit of resilience. (26)

ACADEMIC PERSPECTIVE ON FOOD SYSTEMS RESILIENCE – IMPLICATIONS FOR SYSTEMIC RESILIENCE

Even within the limited field of food systems research and governance, there is no consensually agreed-on definition for systemic resilience. (26) Drawing on initial work by Maleksaeidi and Karami (2013) (39), one of the first conceptual papers by Tendall, et al. (2015) (19) defines food systems resilience as a complementary concept to sustainability. Sustainability is broadly understood as the capacity of a system to achieve the current goals without restricting the future capacities within the system to achieve the same goals. Resilience of the food system, then, is understood as the dynamic capacity to maintain its functions over time despite the existence of shocks and stressors. (19, 39, 40)

The faculty on global systems points to several issues relating to the extant assessments of systemic resilience in the context of the global food system. *Firstly*, scholars generally agree that systemic resilience constitutes a concept of multi-dimensional and multi-scale nature. (24, 26, 35) Yet, studies (notably on food security) have been mainly conducted at the household or community level, focusing on a specific socio-economic group, livelihood, or geographic location, or considering a specific environmental or ecological context. (19, 24, 26, 35) While data, mapping and analysis capacities, as well as ability to speak to all involved stakeholders, justify and explain this local focus of existing studies, it is important to consider interactions with national and global scale, as well as consequences of local specificities for the transferability of insights. Due to complexity, as well as interactions and trade-offs within the panarchy of the system, insights on one scale might not be meaningful on different levels and measurements on higher scales can lead to very different results for the same system. (24)

Nevertheless, a few emergent works are spearheading cross-scalar analyses of food system resilience. A recent study by Béné et al. in 2023 (42), for instance, incorporates the potential for ripple effects from international supply chains into their framework for the assessment of local level resilience. Another way of analysing the impacts of global dependencies is analysing the resilience properties of the trade and dependency network from a global perspective, as done by Puma, et al (2015). (9) However, as food system resilience on the highest scale (i.e. global level) relies on the dynamics of the lower scales (i.e. national and sub-national) (19, 35), behaviour of lower scales may need to be explicitly included to understand its systemic resilience. The question remains, whether resilience on lower scales is necessary to achieve resilience on the highest scale, or whether a self-organising behaviour within the panarchy of the system should allow for some non-resilient behaviour at lower scales. (32, 34, 36) For instance, Seekell et al. (2017) justify deliberate yield gaps (refraining from maximising local production) as a relevant strategy to buffer production shocks through maintaining the ability to increase local production. However, this means that these capacities are not exploited to feed the current population and hence require a certain level of inefficiency. (43)

Secondly, network theory and research on cascading risks in other fields have found emerging properties of complex systems, which can only be explained by the structure of networks. (44) Hence, successful design, implementation and management of resilience-strengthening policies necessitates acknowledgement of the complex interactions across scales and the concomitant implications. (19, 24, 26) Missing policy guidance and coordination relying on the resilience-building of individual actors might lead to trade-offs which endanger the resilience of other actors, or threaten the resilience of the overall system, including future generations. (20) Here, an example can be drawn from the resilience-building activities of farmers, processors and retailers within the UK's fresh fruit and vegetable sector. Higher input flexibility of UK food processors and retailers through short-term contracts have led to the unwillingness of farmers to invest in more resilient practices (here irrigation) as profitability was not guaranteed, thus making the overall system more vulnerable to water scarcity. This example highlights the importance of coordinated action under a consensually shared understanding of resilience amongst key stakeholders. (45)

Moreover, network research has identified specific characteristics leading to an increasing risk of cascading effects. For example, small world graphs (characterised by short distances between neighbours of any given node) have been proven to enable a faster spread of diseases along nodes, as well as robust-yet-fragile behaviour (displaying a resistant behaviour to most shocks, but if a critical node is hit the whole network is affected). (46,47) Therefore, monitoring the network structure and its main characteristics enables the identification of conditions rendering the food system prone to cascading effects and systemic failure. This knowledge may be used to establish early warning signs and identify the need for policy measures to address the detected effects (48), as demonstrated in a study by Burkholz and Schweitzer (2019). (18) Equally, resilience capacities, such as redundancy, diversity, flexibility, connectivity, anticipation, self-efficiency, and access to insurance or formal credit might be monitored to estimate the system's preparedness for risks. However, evidence remains sparse on how much those characteristics enhance resilience quantitatively. (24)

Thirdly, studies examining food system resilience have mainly focused on limited outcome dimensions, such as food security in emergency situations. (19) In addition, such works often focus solely on energy density, without addressing implications for dietary diversity and micronutrient adequacy. (22) A pivotal issue here is that food systems resilience and food security are used interchangeably and without further explanations. (35, 43, 49) (For a noteworthy exemption, see Tendall et al. (2015). (19)

However, to progress toward systemic resilience in the global food system, it is paramount to consider all *outcomes* - and not only those related to food security. Tendall et al. (2015) argue that requiring 'to provide sufficient, appropriate and accessible food to all over time' (19) in the definition of food systems resilience implicitly requires all food system dimensions (e.g. social, economic and environmental) to yield sustainable outcomes. However, assessing resilience across different time frames accurately requires a wholesome understanding of key drivers and their potential negative impacts across different system dimensions from short to the long term. For instance, a retrospective look shows that the global food system has improved significantly in addressing undernutrition and hunger over the last decades1 by nearly tripling its productivity between 1961 and 2011 and could therefore be deemed successful in achieving food security and resilience. However, the very same features driving this productivity (industrial farming methods, wide-spread use of fertilisers and pesticides widely adopted under the green revolution) have been equally associated with dramatic negative outcomes in terms of environmental degradation, now threatening food security in the long run. (20)

Fourth, some parts of the system causing undesirable outcomes, like biodiversity loss, might themselves be change-resistant. Oliver, et al. (2018) list 21 mechanisms across the areas of knowledge transfer, economic and regulatory issues, sociocultural effects, and biophysical constraints that hinder food system transformation needed to generate positive outcomes across its different dimensions. (20) The definition of systemic resilience within the food system should therefore include some notion of outcome desirability and recognise the global food system needs to overcome negative 'lock-ins' (e.g. unsustainable farming practices) to build long-term resilience and sustainability. This means that for some activities and parts of the food system robustness to change needs to be decreased actively to achieve resilience.

INTERNATIONAL ORGANISATIONS AND THEIR VIEW ON SYSTEMIC RESILIENCE WITHIN THE FOOD SYSTEM

Besides scholars across different disciplines, national governments, government bodies and domestic civil society actors, different international institutions are involved in researching and managing food systems and food insecurity. Some of the leading international actors include the World Food Program (WFP), Food and Agriculture Organization (FAO), the World Bank, and the World Health Organization (WHO). Against the background of the COVID-19 pandemic and the impacts of the Ukraine war, resilience and resilience-building have gained increasing traction as key concepts among international organisations in ensuring global food security and preparing against increasing risks deriving from climate change, biodiversity loss and environmental degradation. (50–55) This section takes a closer look at the views and approaches to systemic resilience in the global food system, as adopted in key reports by leading international actors in the field.

Despite discrepancies in framing risk and resilience, institutions such as the WFP and FAO share the same view on the urgency of a multi-hazard and multi-sectoral approach to managing risks and building resilience within the food system. (50, 56, 57) International organisations also stress the importance of systematic analysis and development of early warning systems for natural disasters and shocks. (56) They emphasise, in particular, the increasing risks caused by climate change as one of the major threats to the food system. (56, 58–60) Furthermore, as reflected in the 'Second Joined Statement by the Heads of FAO, IMF, WBG, WFP, and WTO on the Global Food Security and Nutrition Crisis' (2022) (61), there is an increasing understanding that coordinated action and food system transformation are needed to achieve sustainability. (50)

Furthermore, the Sendai framework – ratified by the UN member states at the World Conference on Disaster Risk Reduction in 2015 – is often adopted as a guiding set of principles in their publications on building resilience in the food system. (53, 56, 59) The framework aims to increase understanding of disaster risks, strengthen disaster risk governance (on regional, national, and global level), increase investments in risk reduction, enhance disaster preparedness and implementing a 'Build Back Better' approach to recovery. 62 In line with the Sendai Framework, the need for strengthened international cooperation and coordination in building resilience and disaster response is emphasised. (56, 57, 62) One tangible example of inter-institutional resilience work undertaken by international organisations is the ‘Rome-based Agencies Resilience Initiative’, operated under the cooperation of the WFP, FAO, and IFAD. International actors have also increasingly recognised resilience-building as a cost-effective measure to reduce expenditure on disaster responses and emergency aid. (53, 62)

However, in the context of their operational work, international organisations often address systemic risks in a siloed and incomplete manner. FAO (52) and WB (60) reports, for instance, focus primarily on agricultural resilience, reducing food loss and waste, and developing strategies to support resilience building and addressing inefficiencies in agriculture. Other parts of the food system including processing, storage, retail, waste, loss across the supply chain and consumption patterns remain underrepresented, despite being prone to be affected by shocks (63) and playing a significant role in driving the unsustainability of the system. (64) Additionally, despite advocating for structural change, transformation efforts suggested by international organisations often remain narrow, and focus on improving agricultural practices (including through innovations like precision agriculture and irrigation). This mirrors a common trend in food systems literature, which pays little attention to the drivers of food system change, feedback mechanisms that supports or hinders food system transformation, or power and bargaining relationships between different stakeholders. Moreover, risks associated with malnutrition from overconsumption and the far-reaching consequences of poor dietary habits within industrialised economies are hardly mentioned in the reports of international institutions. This reflects the broader tendency in food systems reports to overlook the connection between nutrition and health outcomes, notably regarding non-communicable diseases. (65) As an exemption, the World Bank 2022 Annual Report promotes healthy and sustainable diets as an objective within its ‘Food Systems 2030 Theory of Change’. (60)

Furthermore, while repeatedly calling for a systems view and ‘systemic solutions’ to strengthen policy practice (57, 60), leading international organisations continue to understand resilience primarily as the *resilience of the vulnerable populations* affected by shocks and disasters (e.g. small farmers, or people already affected by hunger) – not as *systemic resilience of the entire food system*. (1, 58). While protecting the most vulnerable is rightly a key policy priority, adopting a narrow focus that omits the food system’s structural properties and their implications, such as cascading risks through high dependency on imports, ultimately fails to address the root causes threatening food system resilience. Furthermore, while the complexity and interconnectedness of the food system are often mentioned as a risk factor in the reviewed reports, global analysis of network structures and interventions addressing risks are hardly mentioned. Instead, strategies often focus on the country level, especially in Low- and Middle-Income Countries (LMIC), and very limited attention is being paid to High Income Countries (HIC). Consequently, problems arising from highly specialised food systems and structural issues in HICs (such as high concentration of production on a few breadbaskets, or dominance of large agri-food businesses) remain largely unaddressed. (55, 57)

Finally, reports by international organisations have lacked attention to the coincidence of threats (e.g. the co-occurrence of a climate extreme and the consequences of biodiversity loss). (66) Despite frequently referring to climate change and biodiversity loss, they remain equally silent on the issue of crossing tipping points with potentially irreversible consequences for human and Earth systems.

To enable international coordination and cooperation, establishing an international research committee (equivalent to the Intergovernmental Panel on Climate Change; IPCC) for food systems research and suggesting interventions for systemic resilience can help effectively drive renewed thinking and policy practice furthering food system transformation toward increasing sustainability and resilience at the global level. (66)

SUGGESTING A DEFINITION FOR SYSTEMIC RESILIENCE OF THE FOOD SYSTEM

Four key questions should frame resilience assessments (67):

1) Resilience for what?

2) Resilience to what?

3) Resilience from whose perspective (or on which scale)?

4) And resilience within which period?

In this report, we focus on the systemic resilience of the global food system, which relates to whether the individual actions of its actors (functioning) or its final outcomes (functions) should be made resilient. (7). Focusing on resilient functioning might overemphasise bounce-back responses and exclude adaptation and transformation, which alter the system functions. In contrast, conserving the outcomes of the system allows for the self-organisation of (parts of) the system, as long as goals such as food security are achieved (e.g. by shifting distribution and consumption patterns so that less food needs to be produced overall to feed the population). The primary raison d'être of the food system is to achieve food for all, whereas its functioning is shaped by this quest. It is the *function* rather than the *functionality* that should be preserved and restored by resilience. Hence, following previous studies (7, 68), we base our definition of systemic resilience on outcomes across the different dimensions (economic and social, food and nutrition safety, and environmental sustainability) of the food system.

The second question – 'resilience to what?' – refers to the risks by which the current (and future) food system might be affected (see Section 3). In general, the aim of building systemic resilience is to make it resilient to systemic shocks (which may be multiple and occur sequentially or simultaneously, with amplifying and cascading effects) and prevent a major collapse. As such, the focus on shocks remains broad, and is not limited to any specific type(s) of shocks. These unforeseen shocks or effects might be underestimated in public perception, research literature or models and imply a certain level of irreducible uncertainty. (19, 27, 30)

There are different entry points to the third question – "resilience from whose perspective?" (7, 67) – Tendall, et al (2015) (19), for instance, point to 1) national or regional food systems, 2) individual food value chains of selected commodities or 3) individuals (perspective adopted in most of the literature). (35,43) To include systemic risks, we argue that a global and holistic perspective needs to be adopted to fully capture the impacts of cascading effects as well as feedback loops within the global food system.

The final question relating to timeframe is partially addressed by Oliver et al (2018), who assert the importance of a holistic and long-term approach to conceptualising and building food systems resilience, embedding a broad range of outcomes for the whole of society and the environment. Short-term interventions might be unsustainable in longer time frames and result in policymakers and stakeholders accepting trade-offs that endanger the food security of future generations. (20)

Box 2. Definition Systemic Resilience of the Food System

Systemic resilience of the food system is its capacity to prevent systemic risks and ensure its key outcomes (economic, social, environmental and food security) are sustainable despite the impact of stressors and shocks over time.

This systemic resilience definition is equivalent to maintaining the key functions (economic, social, environmental and food security-related) of the system despite the impact of shocks (as by Fanzo et al. 2021[24]), while explicitly asking for assessment of the sustainability of its outcomes. Even though not explicitly built on normative principles, this definition includes a normative perspective, as many of the negative outcomes associated with the current food system (such as biodiversity loss, environmental degradation, and health risks) are increasing systemic risks (see Figure 2) and are required to change. However, being not explicitly based on normative ideas, this definition allows for self-organization, transformation, failure and experimentation at lower scales, which allow the system to develop and permanently adapt to new challenges as they arise. At the same time, removing risks completely is impossible and some level of risk of a total system collapse will always remain within an interconnected and global food system. As uncertainty limits our abilities to understand and measure tail risks, there will always be shocks and cascading effects not covered in the risk assessment and prediction. Furthermore, preparing for every possible risk is more costly than justifiable, and there will be a point at which risk has to be accepted. Overall, resilience is a never-completed process requiring constant monitoring, prioritising of actions and adaptation to changing circumstances.

3. SYSTEMIC RISKS IN THE FOOD SYSTEM

In an increasingly interconnected and interdependent global food system facing a multitude of conflicts and extreme weather events, the frequency of shocks has been steadily rising over the past 50 years. (5, 21) The global food system – itself a key driver of adverse ecological effects – is under stress due to the negative impacts of climate change and environmental degradation. Higher temperatures, water scarcity, pollinator loss and soil degradation are leading to less land available for food production, higher prices, and food insecurity. (22) **This section presents current threats to the food system, differentiating between shocks and stressors, and shortly discusses the implications of potential coincidence of threats.**

THREATS TO THE FOOD SYSTEM – SCHOCKS AND STRESSORS

Threats to the food system can be classified into two different categories, shocks and stressors, which are either endogenous or exogenous to the system. To estimate risks associated with stressors and shocks, they need to be understood and quantified in terms of likelihood, severity, spatial and temporal extent, detectability, and perception. (7)

A number of exogenous shocks are highlighted in the existing literature. Environmental shocks include climate effects, such as extreme weather, which can be separated between fast onset events like hurricanes, or storm surges, and slow-onset events like heatwaves or droughts. (8) Extreme weather can affect not only production itself, but also processing, trade and retail, by causing infrastructure damage, for example on ports, or hindering transport, as exemplified by the impacts of the long drought periods in 2024 on shipping through the Panama Canal. (69,70) Environmental shocks also include nature shocks, such as pests or diseases, which might be external or foodborne. Their impacts range from direct effects on food production causing yield loss through negative effects on plants or livestock (e.g. the locust outbreak in East Africa in 2019 and 2020 (71), to indirect effects on people working in the food system or consumption patterns (as during lockdown measures introduced in the COVID-19 pandemic). (72) Other causes of shocks to the food system include social and political conflicts, ranging from international (e.g. geopolitical events and international conflicts, such as Russia's war against Ukraine) (11) to local (such as local food safety scares). (73)

Box 3: Shocks to the Food System

Shocks are abrupt events that may be completely unexpected or disturb the system in an unforeseen way. Shocks vary in the probability of occurrence, as well as the severity and scale of impact [7]. Shocks are mostly, but non-exclusively, exogenous to the system and can affect the whole, or only parts of the system. A food-borne microorganism spreading unexpectedly represents one example of an endogenous shock.

The food system can also be disturbed by an economic or financial shock, such as the financial market crash in 2008 (74), typically leading to long- or short-term cost spiralling. The food system is especially vulnerable to rising oil prices due to fossil-fuel-based energy supply in agricultural production, as well as tight coupling to fertiliser and chemical prices. (66) Economic shocks can affect both the supply (e.g. through rising production costs) and the demand side (e.g. through income loss or migration). (75) Relatedly, disruption in trade or supply chains can cause price spikes or supply changes in other parts of the food system affecting calorie consumption and nutritional intake globally. (7, 19, 66) Heavy reliance on very few chokepoints in international trade leads to high systemic vulnerability when any of the central nodes in the network are affected, e.g. by extreme weather. (66, 69, 76)

Moreover, food price crises are often associated with export bans in producer countries that seek to ensure domestic food security in the context of shocks, leading to further cascading effects and rising prices (as exemplified by India's export bans on rice in 2022 and 2023). (77, 9, 15, 78) A 'multiple breadbasket failure' represents another prominent food production shock that can cause a systemic risk to the global food system. It refers to a major yield reduction in annual crop yield in multiple breadbasket regions. Globally important breadbaskets are key production areas responsible for producing large amounts of grain for domestic production and export, and hence sustaining the diets of many people. When affected by a shock, such breadbasket areas may experience production failure and cause significant humanitarian, economic and/or political crisis, given their strategically important role in driving global food security (e.g. being a donor country to food insecure regions). (79)

However, it is noteworthy that food system shocks are not associated only with negative consequences and systemic risk. Transient periods of unusual conditions can open windows of opportunities for desired food system transformation and a renewed approach to governance helping to overcome lock-in effects. (20, 68)

Furthermore, whether a shock leads to a systemic failure is highly dependent on the vulnerability of the system, which is largely defined by its capacity to absorb shocks and self-organise to adapt to changing conditions. (80) These capacities are determined by the state of the system and are limited by stressors.

Endogenous stressors include, for example, sole optimisation for cost efficiency which can lead to unsustainable practices and reduction of resilience capacities, such as redundancies. (20,81,82) In contrast, external chronic stressors such as demographic changes affect the demands for the food system (e.g. providing nutritious food for growing populations). However, here, the distinction between external and internal stressors is blurred as external stressors can directly change internal activities or be indirectly influenced by the food system itself – albeit to a more limited extent.

Mixed stressors are significantly, but not exclusively, driven by the food system. Environmental stressors include mixed drivers such as climate change, biodiversity loss (and the associated loss of ecosystem services), water scarcity and land degradation, pollution and waste management, as well as internal factors comprising changes in landscape-level land use, and agrochemicals use. (7,8,19,20,83,84) Socio-economic drivers comprise dietary shifts and consumption patterns, changes in commodity prices, technology and demographic change (85), as well as urbanisation. (7,85,86) Furthermore, alterations to regulatory arrangements and trading agreements might stress the food system unintentionally through direct or indirect intervention. (7)

Even though stressors act on long time scales and are associated with gradual change, mainly influencing vulnerability and resilience capacities of the global food system, if a tipping point is reached, stress can lead to a drastic change. In such instances, a single or a combination of stressors become sudden shocks to the system. (66) Despite being highly policy-relevant, tipping points remain under-researched, making them difficult to predict and manage. (7,87)

Threats to the global food system can be highly interconnected and triggered by, or lead to, compounding effects, which is the situation in which several risks or their impacts overlap or co-occur. For instance, there is a potential link between the effects of climate change and social unrest (e.g. triggered by climate-induced migration), their combined effect increasing the potential to lead to a food system collapse (e.g. if production or labour are affected drastically or supply chains are disrupted) – locally, regionally, or even globally. (66) Hence, besides evaluating individual stress indicators of actors, it's crucial to assess the combined stress levels within the entire system.

4. INDICATORS FOR MEASURING FOOD SYSTEM OUTCOMES

In this section, we discuss the importance of assessing the outcomes of the food system across all its dimensions to gauge its sustainability, and present different methodological approaches for doing so. We also address persisting challenges for robust assessments, including data availability issues.

EXISTING FRAMEWORKS FOR ASSESSING THE SUSTAINABILITY OF GLOBAL FOOD SYSTEM OUTCOMES

To our knowledge, the extant literature on the global food system currently lacks a set of specific indicators for assessing systemic resilience or measuring the effectiveness of resilience-building interventions. Whether the food system is demonstrating resilience to global shocks may be assessed by monitoring the dynamics of food system outcome indicators under different risk scenarios. However, it is important to note that although outcome indicators can generate information on food system dynamics under shocks and potential risks for future resilience (by identifying unsustainable practises and associated stressors), their development needs to be monitored over time – as a one-off "snap-shot" they constitute an insufficient tool to examine resilience capacities and the likelihood of failure of the food system.

That said, food system outcome indicators can act as guiding stars for the design and implementation of interventions to build resilience and to spur transformation in the food system. (68) They can be used to estimate the expected outcomes of policy measures to identify possible trade-offs and unwanted consequences, and are thereby essential to informed policymaking. One example of indicator-based scenario analysis providing policy advice for individual countries is the work by Chaudhary et al. (2018), who use different dietary scenarios to estimate the influence of dietary shifts on food system outcomes, measured in 7 different dimensions through 25 different indicators. (88)

Several conceptual and methodological challenges have to be considered when selecting appropriate indicators for food system outcomes: 1) they have to be representative in terms of global coverage, 2) they have to be selected in a transparent and justified way, avoiding replication and/or cross-correlation which might skew later judgement, 3) they have to be rigorously measurable, and 4) if a composite metric is defined, the calculation should be appropriate based on existing knowledge. (25)

Assessing resilient behaviour over time by continued monitoring of food systems outcomes across all four dimensions (food and nutrition security, economic, social and environmental) is imperative. Given that resilience secures the functions of the food system in all its outcome dimensions over time (7, 25), adopting sustainability indicators as part of such monitoring is important. (19) Furthermore, by distinguishing resilience from mere resistance to change, sustainability indicators can highlight current shortfalls in the system and identify areas of stress leading to potential shocks in the future (e.g. persistence of nature degradation through agriculture). (20) On rare occasions – to prevent major failures – unsustainable parts of or structures within the system might need to be protected (e.g. an unsustainable but temporarily vital supply chain).

Drawing on a comprehensive literature search, Béné et al. (2019) present a list of 27 indicators for effectively quantifying food systems sustainability in different dimensions and subdimensions. We suggest this collection of indicators as a starting point for further food system outcome quantification, given that they cover (at least to some extent) all food system dimensions and the availability of indicators at global scale. However, data on food systems is often limited to agriculture, especially for economic and social outcomes. Therefore, some indicators listed below in Table 2 can only act as proxies and increased monitoring in the other food system sectors (such as processing or packaging) is required for a more comprehensive picture. This framework, as based on existing indicators, misses aspects of the food system which are lacking appropriate quantification. (25) One such example is the economic health of the various actors in the food chain – necessary for sustainable, continuous activities and thereby greatly impacting food system resilience. (22)

Dimension	Sub-dimension	Category	Indicators	DP	Source
Environ-mental	Air	Quality	Greenhouse gas emissions in total agriculture	C	FAO
	Water	Quality	Water pH	C	GEMStat water quality database
		Use	Agricultural water withdrawal as percentage of total renewable water	P	FAO
	Soil and land	Quality	Soil carbon content	C	FAO
		Use	Agricultural land as % of arable land	C	FAO
	Biodiversity	Wildlife (plants, animals)	Benefits of biodiversity index	C	The Global Environment Facility
			Crop diversity (Calories diversity measured by Shannon index)	C	[89]
	Energy	Use	Agriculture and forestry energy use as % of total	P	FAO
Economic		Financial performance	Agriculture value-added per worker	P	WB
		Employment rate	Agriculture under-employment	P	ILO
		Economic Distribution	Gini index for land distribution & tendency	P	GRAIN organization
Social		Gender equity	Labour force participation rate, female (% of female population ages 15+)	P	WB
		Inclusion	Predominant fair-trade organizations and producers	P	Fairtrade International
			Employment in agriculture (% of total employment)	P	WB
		Availability	Per capita food available for human consumption	C	Dupon_GFSI source FAO

			Food consumption as share of total income (% of total household expenditure)	C	Dupon_GFSI_ National Accounts; UN
		Access	Estimated travel time to the nearest city of 50,000 or more people	C	EC
			Access to improved water resource (% of total population)	C	FAO
		Urbanization	Access to electricity	C	WB
			Price volatility index	C	FAO monthly CPI
	Food Security	Stability	Per capita food supply variability	C	FAO
	Food Safety		Burden of foodborne illness (number of cases)	C	WHO
	Food waste and Use		Food loss as % of total food produced	C	Dupon_GFSI source FAO
		Diet	Diet diversification	C	FAO
		Under-nutrition	Stunting, children aged < 5 years stunted	C	WHO
		Overweight & Obesity	Prevalence of obesity (% of the population, over 18 y of age)	C	WHO
Food and Nutrition	Nutrition	Hidden Hunger	Serum retinol deficiency	C	WHO

Table 2: Food System Outcomes Indicator as in Béné et al. (2019). (25) Some indicators can only act as proxies for the suggested subdimension of one of the food system outcomes, which is indicated as the Degree of Proxy (DP) with P for proxy or C if the quantification is holistic.

Furthermore, Hebinck et al. (2021) (90) criticise the indicators employed by Béné et al. to capture social welfare, as they do not cover inequitable power relations (access to knowledge and technologies, financial and natural resources and chances to participate in decision-making) within the food system; distribution of environmental risks and benefits; or material and non-material contributions of nature to people's livelihoods. Additionally, the authors argue that to effectively support policymaking requires an assessment of possible trade-offs, mediation of diverse value judgements and integration of different stakeholder perspectives into a 'shared vision'.

In an attempt to rectify these gaps, Hebinck et al. define a set of desirable indicators for sustainability of food system outcomes, incorporating expected impacts of policies (as evaluated through different models) as 'the (lack of) progress vis-a-vis key sustainability goals' based on the United Nations Sustainable Development Goals (SDGs). As such, their framework allows for assessment and discussion of the expected outcomes of policy strategies, highlighting trade-offs that may be required between different outcome dimensions. However, Hebinck et al acknowledge the lack of sufficient, up-to-date data for many of these indicators.

Finally, it is noteworthy that science-based sustainability targets (such as those adopted by Hebinck et al.) represent a compromise between scientific evidence, societal norms, and political views. This means that reaching the target does not automatically correspond to staying within physical planetary boundaries or enabling human thriving for all.

A DOUGHNUT FRAMEWORK FOR FOOD SYSTEMS SUSTAINABILITY AND RESILIENCE

Kate Raworth introduced the concept of the safe and just Doughnut space in her award-winning publication 'Doughnut Economics' in 2017. (91) Though initially applied to the context of the global economic system, the insights and analytical approaches presented by Raworth can be adopted to other complex global systems, such as the global food system. In this report, we stress the importance of achieving the safe and just space within which humanity can thrive in the context of food system activities.

Box 5: Doughnut Economics

The concept of Doughnut Economics was developed by Kate Raworth [2] to outline the safe and just space within which humanity can thrive while staying within the social and ecological boundaries (see Figure 3).

The outer circle is defined by the ability of our Earth's life-supporting systems to maintain their functioning and sustain Holocene-like conditions, which are the only proven conditions supporting contemporary human societies. Crossing those boundaries could alter Earth's functioning dramatically and lead to much less hospitable environmental settings for humanity [92]. The nine planetary boundaries resemble limits for anthropogenic perturbations of critical Earth-system processes to stay within the 'safe zone' in which major changes in Earth system functioning only occur with low probability.

The inner boundary of the Doughnut is based on twelve indicators which quantify the internationally agreed minimum standards for human well-being, as given by the UN Sustainable Development Goals (SDGs). Falling short in these dimensions means that essential conditions, like clean water or safe food, are not met.

We argue that the 'safe and just Doughnut space' can serve as a guiding concept for high-level policymakers and stakeholders to assess the current outcomes of the food system on society and planet. The Doughnut framework, illustrated in Figure 3 below, allows to quantify the sustainability of food system outcomes on global level, while leaving room for self-organisation and inefficiencies – as long as the food system remains within the Doughnut space. Undesirable environmental outcomes of the food system are represented by crossing planetary boundaries, while shortfalls in social, economic or food security are represented by crossing the social foundations. This underlines the difference between bio-physical and socio-economic impacts, which lead to different risks and require different policy responses. The social foundations also put emphasis on the fact that the food systems aim is ultimately to provide accessible, nutritious, and save food to everyone while simultaneously achieving and sustaining sustainable economic, social and environmental outcomes. In addition, the Doughnut framework offers the possibility to visualize (un)resilient behaviour, which is represented by the ability of the system to stay within the Doughnut space over time despite shocks and stressors.

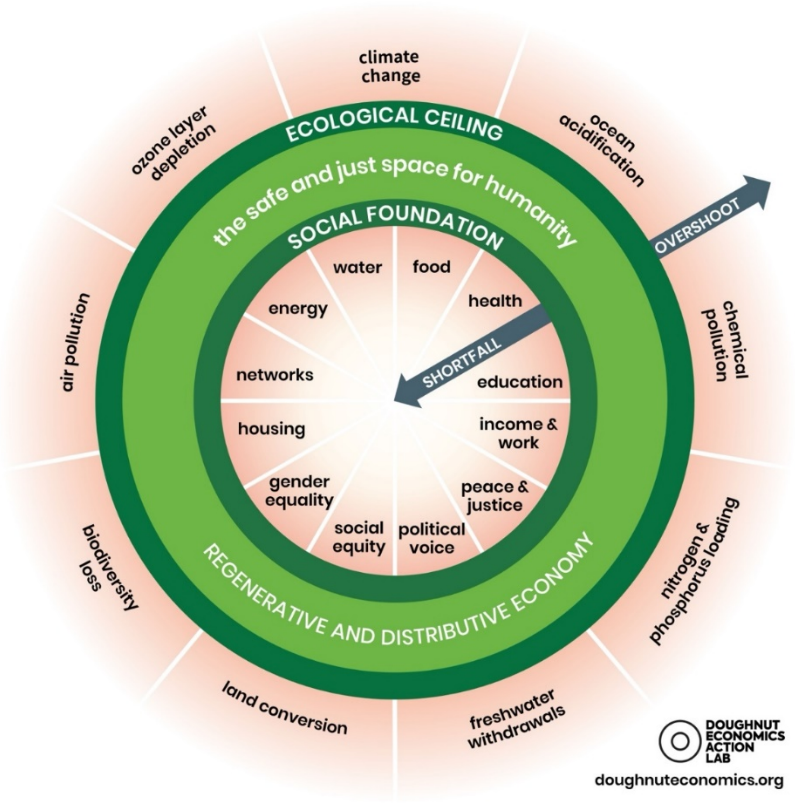

Figure 3: The Doughnut framework of social and planetary boundaries. It defines the space for a regenerative and distributive economy which allows humanity to thrive, by ensuring everyone's social foundations are met, while remaining within the planetary boundaries to ensure sustainability over time. Shortfall in the social foundations causes human suffering, while overshooting planetary boundaries drives our planet to leave Holocene conditions, leading to inestimable risks. (2)

Within the Doughnut framework, the impacts of shocks to the food system are visible through (temporary) crossing of boundaries. Different characteristics of risks resulting from shortfalls in social dimensions and shifting outside of the 'safe space' of planetary boundaries are reflected. Climate change, environmental degradation and biodiversity loss generate a multitude of direct (extreme events, pollinator loss, etc.) and indirect (pest and disease spreading, water availability, etc.) risks to future food systems. Furthermore, these risks are highly interlinked, leading to great probability of coincidence of risks. (66) Alterations in Earth's functioning which move it beyond Holocene-like conditions can have drastic and non-reversible consequences. Yet, there is great uncertainty in our understanding of how physical tipping points might affect our ability to maintain favourable conditions for food production and processing. Furthermore, our current systems will need time to react to early warning signs, such as critical slowing down, increasing variance and fast changes between the states of the system. Uncertainty over tipping points and the need for reaction time are both reflected in the precautionary principle deployed for defining planetary boundaries. (92)

However, it should be noted that the Doughnut framework as it stands quantifies some food system outcomes and activities only indirectly (e.g. animal welfare, yield gains or stable commodity prices). It remains to be discussed to which extent they should be directly included in the framework to make it suitable for food systems assessments. Also, economic and financial outcomes – together with their associated risks – remain excluded from the Doughnut, initially developed as a model for a sustainable economy. However, monitoring the economic and financial sustainability and resilience of the food system is essential for mitigating future risks and building resilience capacities.

Table 3 provides an overview of the three main indicator frameworks for (potentially) quantifying sustainability of food system outcomes presented in this report. These three frameworks are by no means a comprehensive overview but are used to exemplify the benefits and limitations associated with a data-based (Béné et al. (2019) (25), a comprehensive and policy goals-based (Hebinck et al. (2021) (90) and a planetary boundary and social foundations-based approach (Raworth (2017). (91)

Framework Example	Underlying Concept	Benefits & Use Cases	Limitations
Global map and indicators of food system sustainability[25]	Based on existing indicators (identified through literature research). Selection criteria: 1) No cross-correlation 2) Conceptual relevance 3) Global scale 4) Global validity 5) Recent data availability 6) No latent variables 7) Clear methodology 8) Single dimension indicators 9) Comparability across countries	• Includes indicators for all food system outcome dimensions. • Data availability is ensured, as it was explicit selection criterion. • Explicit check for correlation between indicators & optimisation for indicator coverage. • Rigorous selection process with stringent calculation method.	• Only proxies for social and economic dimensions (mainly based on agriculture). • No animal welfare indicator. • Unequal number of indicators for each output dimension & several under-represented aspects.
Sustainability Compass[90]	Based on an interdisciplinary review of food systems perspectives, metric-based frameworks & stakeholder consultation. Indicators for food systems dimensions are combined with existing 'science-based targets' to sustainability scores to quantify policy outcomes. Science-based targets reflect the negotiation process between policy, science, and society. Selection criteria: 1) Pragmatic solutions (use of proxies) 2) Uniqueness of indicators 3) Relevance of indicators	• Includes all food system outcome dimensions & subdimensions. • Aspects of social welfare (especially social equity) and economic stability are more comprehensively covered. • No compromises due to data availability or previous existence of indicators. • Inclusion of multi-stakeholder perspectives and different kinds of knowledge (apart from scientific priority setting). • Visualisation as progress towards agreed policy goals (facilitating multi-stakeholder dialogue, identification, and management of trade-offs). • Trade-offs & priority setting visualised directly & over time. • Tool built for supporting policy processes and enabling multi-stakeholder cooperation.	• Data is not (yet) available for all indicators suggested. • Indicator suggestions are given for European coverage only (need to be adapted to global level). • No clear inclusion/exclusion criteria for indicators & stringent explanation of selection as well as weighting of indicators (identified through multi-actor deliberation). • Science-based targets are a negotiated compromise between scientific evidence, society, and politics and do not necessarily sufficiently address the problem. Hence, reaching the target does not automatically refer to reaching sustainability or staying within planetary boundaries, etc.
Doughnut Framework[91]	Outer circle: based on planetary boundaries framework & precautionary principle. Inner circle: social foundation based on SDGs.	• Explicit inclusion of uncertainty in knowledge about tipping points & time needed for reaction (early warning signs). • Visualisation of difference in consequences for crossing ecological and social foundations. • Simple but direct dashboard with globally accepted indicators to quantify sustainability of current food systems outcomes.	• Framework was not designed for the food system explicitly and indicators are not tailored towards food systems outcomes (proxies would be needed to see influence of food system on those general indicators). • Food systems variables (yields, dietary choices, loss and waste) not directly represented. • Economic dimension not explicitly covered.

		• The framework could be used to visualise where the outcomes of the food system leave the 'safe and just space' in all (not restricted to food systems outcomes) dimensions.	• Data availability issues for some of the indicators (functional diversity, atmospheric aerosol loading, novel entities).

Table 3: Different frameworks for quantifying the sustainability of food systems outcomes. The underlying approach has direct consequences for the selection of indicators, as well as the design of derived metrics and visualisation. The different examples selected here are chosen to represent different approaches (data-based, policy-oriented and overview-oriented) and are a non-comprehensive list. For a successful representation, modelling, and quantification of food system resilience, a combination of different methodologies might be desired.

DATA AVAILABILITY – CURRENT STATE AND CHALLENGES FOR SYSTEMIC RESILIENCE ASSESSMENT

As explained above, limitations in data availability remain a key issue restricting our current abilities to quantify systemic resilience within the global food system.

Many indicators used for estimating status, outcomes, and stressors on, as well as impacts of, the food system are based on data made available through UN agencies such as the FAO Food Balance Sheets (FBS). (21, 22, 25, 88, 93,94) However, there are serious data limitations, especially in respect to global coverage. For instance, country coverage in FAO data varies from indicator to indicator, and data from other institutions often have even more restricted availability. (25)The number of possible indicators is restricted by the number of countries each indicator is available for, but as different indicators cover different subsets of countries, overlap between those subsets restricts further use. For example, the 27 indicators selected by Béné et al. (2019) to measure food system sustainability – and discussed in this report for the monitoring of food systems outcomes – are as a set only available on a subset of 16 countries (despite each of them individually having a much broader coverage). (25)

Additionally, many indicators can only act as proxies for functions of the food system (especially in the economic and social dimension) as they are available for agriculture only. (25, 90) More comprehensive monitoring of the food systems, especially in other sectors such as transport, processing, retail and distribution, will be key. Data coverage remains particularly scarce in LMIC, but data gaps in sectors different from agriculture exist also for HIC. (25)

Furthermore, existing models utilised for food systems scenarios, such as GLOBIOM (95), rely heavily on price and income metrics, because data on non-price incentives for consumer and producer responses are missing. (96) This hinders understanding, assessment, and quantification of non-price driving forces (such as consumer taste, social norms, and convenience) and their influence on aggregate behaviour.

There are also some more specific areas in which data and research gaps present an obstacle to successful quantification, with examples listed below.

- Major gaps remain regarding the **poorest and most vulnerable populations** within the system. Despite existing measures for poverty, the link to income derived from food systems and clear indicators for livelihoods dependent on food are missing. Moreover, data on informally employed workers, as well as women, ethnic minorities, migrants and undocumented labour is sparse, exacerbating their vulnerability to exploitation. (24) Data gaps hinder the successful development and implementation of policy interventions to address these vulnerabilities.

- Data on **seafood production** and its impacts on the food system remains limited as the majority of assessments currently focus on crop and livestock production. (96) The spatial expanse of inland waters and oceans for aquatic capture food production is missing, which makes it hard to identify and conceptualise aquatic 'land-use' and the associated stress to marine and riverine ecosystems. (24) However, there is some emerging work on using satellite data for this purpose. (97)

- Pollution caused by the food system through **run-off and nutrient loss, biocides, air pollution and solid waste** across the food value chain affects several food system outcomes. By damaging the environment, causing health problems, and leading to water and land degradation, it is impacting humans, as well as arable land and water resources. However, data and research gaps are limiting our understanding and ability to quantify damages. (24)

- There is a limited understanding of the **connections between hazards** (e.g. climate events, pests) and their impacts on supply chains, along with changes in the activities of food actors. For instance, to better comprehend the correlation between climate extremes and yield losses, specialised data on agronomic factors like irrigation, pest infestation, or crop varieties is warranted. (98)

- Finally, significant data gaps persist on the (direct and indirect) **impacts of implemented policies**. This restricts the knowledge-base that is required for effective governance of the food system in order to facilitate transformative change and set gold standards and best practices for policy. (24, 68, 79, 99)

5. MODELLING SYSTEMIC RESILIENCE IN THE FOOD SYSTEM

Modelling resilience in food systems serves multiple purposes, including prediction, exploring system dynamics, explaining risk emergence, identifying behaviours and uncertainties, highlighting intervention options, illustrating trade-offs and synergies, pinpointing knowledge gaps, guiding data collection, testing hypotheses, training practitioners, and informing policy dialogue. (100,101) **This section provides an overview of different existing models of the global food system, and discusses their strengths and weaknesses in capturing systemic risks. The use of scenarios for modelling systemic resilience is also presented.**

EXISTING MODELS OF THE FOOD SYSTEM

There is a diverse set of existing global models of the food system. However, they are similar in their focus on specific components, such as agricultural production, land use, and trade. (102–105) Different types of modelling include *correlation modelling* (deriving implicit knowledge on relationships between variables from empirical data), *process-based models* (explicitly describing physical or biological processes), and *expert-based models* (derived from experience and advice of experts and stakeholders, including local and indigenous knowledge holders). (106)

One widely applied approach is simulating the implications of agricultural and trade policies with Computable General Equilibrium (CGE) models. Several big CGE models (GTAP, MAGNET, MIRAGRODEP) for assessing food systems coexist, each with their own set of strengths and weaknesses determined by the intended purpose and associated trade-offs. Example can be drawn from the MIRAGRODEP model. (107) Developed for trade and agricultural policy analysis (based on MIRAGE) (108), it covers both aspects in great detail (including inefficiencies of the tax collection system and an improved demand system), while excluding other parts of the food system (e.g. direct representation of environmental issues). By contrast, the MAGNET model (109) is characterised by modular design allowing for a broader application and adaptability to different types of research objectives. It is a further development from the CGE model GTAP (110) and covers land use, household consumption, livestock, crop production for food, feed and energy, as well as protected areas (and associated emission reduction) and avoidance of deforestation to a high level of granularity. However, the model requires several simplifications, such as the use of constant elasticities over time. Furthermore, MAGNET expresses volumes and substitutions in monetary values rather than in physical terms, which means that consistent changes in composition are not guaranteed with physical requirements (e.g. relating to livestock feed). (111)

There are several points of criticism regarding the use of CGEs in assessing complex systems, such as the global food system. (101, 112–114) CGE models are based on neoclassical assumptions (mechanistic, reductionist approach to the market as the multipotent solution provider; rational consumer and welfare maximisation of individuals represented by materialistic utility; general equilibrium assumption, etc.) for their structure, production and cost functions. This results in limitations in adequately representing the emergence of dynamics within the system, e.g. those arising from feedback or delay. (91, 111, 115)

These underlying principles and assumptions, as well as the associated limitations in adequately representing reality have severe implications for the representation of risks and resilience. (48) One pressing issue is that focusing on rational actors omits the influence of perceived risk and expected gain on actors' behaviour. For example, excluding the role of investors' perceived risks in financing decisions leads to a biased expectation of policy outcomes and can hinder the identification of climate mitigation pathways. (116) Moreover, non-linear aspects, such as changes in exogenously defined parameters or elasticities, during and after a shock or hysteresis (long-lasting effects and slow recovery), are not accounted for. (37,111) Strong assumptions of linear behaviour do not hold in reality and can lead to a serious underestimation of risks. Additionally, transition processes are hardly ever included in models which exclusively focus on the long-run equilibrium, meaning that short-term direct and indirect losses cannot be assessed. (37)

Lastly, equilibrium thinking presumes the existence of a stable, efficient state towards which the food system converges. However, stability in complex systems emerges from the interactions of its components and is maintained through permanent adaptation and learning. (117) Equilibrium thinking – leaving out reinforcing and dampening feedback, delay, and interaction – is thereby unable to quantify self-organising criticalityb and the resulting consequences for systemic resilience. (32) Endogenous effects, which contribute to the gradual accumulation of risks through reinforcing feedback loops, are not accounted for and risks must be modelled solely as exogenous shocks. (118)

Partial Equilibrium (PE) models such as GLOBIOM (104), IMPACT (105) or MAgPIE (102) focus on specific segments of the economy, considering only particular economic flows, and enable a more detailed representation of technology and land use in agriculture. (119) As such, they provide a more detailed understanding of the sector, which may be helpful for policy analysis. (120) For example, GLOBIOM was designed to quantify land use-related topics such as bioenergy policies, deforestation, climate change adaptation and mitigation from agriculture, and includes representation of crops, livestock, forestry, and bioenergy with high spatial and commodity resolution. (104) PEs can be classified based on their structure and integration of economic principles. Shallow structural models are based on supply/demand function with no explicit representation of maximisation of behaviour. In contrast, deep structural models include a detailed representation of technology and require an explicit maximisation behaviour. (119)

Despite providing a more detailed portrayal of agriculture and land use, PE models encounter similar limitations to CGEs. Additional restrictions relate to the implications of significant changes in or shocks to agricultural production, which are not sufficiently incorporated through the simplified representation of the links to the rest of the economy or wider system parts. Moreover, the incompleteness of the models forces them to rely on wider assumptions on the supply and demand side. (119) Critically, they assume that the rest of the economy is unaffected by alterations in the food system. (120) However, this is only reasonable when only minor impacts are to be expected, which is not the case in the context of a systemic failure.

Connecting the food system to the wider Earth and human system can be realised through a linked chain of different models. Alternatively, drivers, nature's response and consequences for human society and well-being can be integrated as parts of one combined modelling framework, which allows for a better representation of feedback between represented

[b] Refers to the system driving its own risk, for example through unsustainable practices which drive the system towards a critical state where a failure or collapse will occur.

components. (106) Integrated Assessment Models (IAMs) capture global interaction between the natural environment and human development. (111) While CGEs have their roots in economic theory and are focused on a representation of human society, IAMs like IMAGE (111) or MESSAGE-iX (121) are hybrid models. They combine human and Earth system modelling to enable a better understanding of global environmental problems arising from human action such as food production, or energy use.

Two different strands of IAMs exist: 1) normative, compact models based on a small number of equations and with limited global coverage for policy optimisation, and 2) descriptive, more detailed models used for simulation analysis and comparison of different policy strategies. (122) IAMs are developed as a fine-balanced trade-off between a detailed representation of all relevant processes (e.g. atmospheric flows or crop growth models) and simplification to ensure computational feasibility, to enable global application and circumvent data availability issues. (111,122) However, to cover food systems, widely utilised IAMs often rely on CGEs or PEs to incorporate agricultural economics, which is then used to estimate land use, as well as environmental impact. (111,121,122) Despite employing biophysical process-based modelling for inputs to these IAMs – to calculate estimated yield loss, for example – they inherit the general problems of CGEs discussed above.

The question of whether a model representation of the food system is useful for policymaking highly depends on the context and the purpose. Some of the typical trade-offs include time requirements and calculation capacity, as well as technical knowledge required for the application and interpretation of model results. One relevant example here is the FABLE Calculator (103), developed for fast projections of food and land-use systems on a wide range of parameter values to estimate alternative development pathways at the country level. As it doesn't demand programming skills, is compatible with nearly all computers, facilitates swift comparisons among numerous scenarios, and maintains transparency in its structure, this tool empowers stakeholders from diverse backgrounds to visually assess current imbalances and threats in national food and land-use systems and hence makes a significant contribution to communication of possible scenarios to facilitate policy engagement. (103) More specifically, in contrast to approaches explicitly modelling interactions with and within the food system, the Calculator is a public mass-balance model written in Excel. Based on historical data, it calculates the outcomes of future scenarios by shifting parameters according to a selected scenario without an optimisation analysis. While there are some limitations dues to reliance on aggregated, deterministic mean projections for countries, as well as underrepresented indicators for social outcomes there have been recent steps towards integrating climate and trade risk for resilience assessment into the FABLE framework. (123)

MODELLING SYSTEMIC RISK – A COMPARISON OF APPROACHES

All modelling approaches presented above are *deterministic* in nature, which means they include a set of equations and deliver the same result when given the same input data. Input parameters based on mean expectations without considering variability (e.g. using only one global temperature rise estimate) remain insufficient for risk assessment, as they require perfect foresight for analysing future scenarios. (124) They can't capture (sometimes short-term and small-scale) stochastic variability within scenarios potentially leading to very different outcomes than expected mean behaviour. Risk-neutral approaches to food systems, not accounting for such variabilities (with low probability but high impact), may lead to inadequate management practices. This was demonstrated in a recent study by

Wildemeersch et al. (2022) on phosphorous load in agricultural watersheds. To account for uncertainties, tools from stochastic analysis can be employed to set accepted risk levels, which in turn helps identify relevant policy strategies to address risks. Defining reliability targets for sustainability can be used to manage the trade-off between desired outcomes of the food system (e.g. production increase or profitability and risk avoidance). (124)

Furthermore, the dynamics of complex socio-ecological systems are shaped by non-linearity and feedback causing emergent properties and (unintuitive) behaviour. 101 To assess consequent risks for cascading shocks and losses, network representations of global food and commodity trade have been used. Some studies (18,125) examine trade dependency networks to capture the effects of export restrictions, typically imposed by individual countries after a production or price shock. Insights from complex systems analysis on basic network characteristics and their subsequent implications on vulnerability to self-propagating state shifts and multiplier effects may be used to assess vulnerability. Puma et al. (2015), for instance, analyse the changing properties of the global food system over time, concluding it evolves towards a '*robust-yet-fragile*' configuration. (9) This characteristic is a well-researched feature of complex and interconnected networks and depends on their underlying structural properties. (47,126) Reliance on a few key nodes, too many connections between nodes, and short-cut connections between nodes (small world trait) are associated with a robust-yet-fragile behaviour. One prominent, tangible example is the 2008 economic crisis; the economic system showed all of the three properties described above before the crash. (91)

Agent-based models (ABMs) simulate the behaviour of individual actors and their interactions within the food system, allowing to explicitly represent feedback, delays, and emergent behaviour. (101) They offer several advantages compared to traditional IAMs, including better coverage of uncertainty, technological change, distribution of effects and bounded rationality of actors, as well as bottom-up emergence of damages instead of a stylised and aggregated damage function. (112) However, limitations in data availability and computational demand have so far restricted these representations to smaller scales. Existing studies have often focused on a country or regional level, quantifying the impacts of disruptions on supply chains within a country or of specific goods. (127–129) Yet, some emerging examples show that these restrictions might be overcome as data availability and processing power improve. (112)

Scenario analysis, stochastic optimisation, network representations and ABMs can be combined to capture emerging properties as well as complex interactions with the food system. Naqvi et al. (2020) use a copula approach[c] combined with a multi-layer network and agent-based modelling to understand the implications of tail-depended shocks on food systems. (37) Copula modelling enables analysis of the effects of non-linear co-dependences of tail-risks across regions, for example in the case of multiple breadbasket failure (37) – which represent a growing risk spurred by the effects of climate change. (130) However, these modelling approaches represent a new development and are not yet widely applied. Furthermore, every simplification of complex systems comes with the risk of hypocognition, which means that important aspects and properties are missed as their importance is not yet known. (131)

[c] Copula modelling is used to model the nonlinear co-dependencies between risks

THE NEED FOR SCENARIO ANALYSIS

Following the definition of *scenarios* proposed by Ferrier et al. (2016, p. 3), we understand scenarios as 'plausible representations of possible futures for one or more components of a system, or as alternative policy or management options intended to alter the future state of these components.' (132) Scenarios offer a key method to gauge potential future developments and options for change as input for modelling, while acknowledging the presence of uncertainty and the unpredictable nature of future events and decisions. (106)

For modelling purposes, different risk and policy intervention scenarios targeting drivers of risk may be used to analyse the consequences of adopted interventions on food system resilience. Such scenarios allow us to better understand future impacts of different resilience-building strategies, raise awareness for unwanted consequences of possible future scenarios (e.g. unabated climate change and biodiversity loss), help design adaptive management strategies and combine and synthesise a broad range of interacting factors and drivers. (106)

6. FOOD SYSTEM GOVERNANCE AND POLICY INTERVENTIONS

Our ability to stir the food system towards a more resilient and sustainable future, while protecting it from a total collapse or failure, is confined by our decisions today. The option space within which we can safely choose between different intervention measures – safeguarding key characteristics of the food system we value and know – is restricted by our actions and inactions in times of growing risks. Swift and coordinated action will be critical to get our food systems into the 'safe and just space' of the Doughnut and make it resilient against systemic risks. **This section makes the case for strengthened global food system governance and provides an overview of key policy interventions to enhance systemic resilience within the global food system**, as suggested in the existing literature. The Safe and Just Decision Corridor (SJDC) framework is introduced as a relevant tool to capture dependencies between policy interventions and their implications for systemic resilience. The section also shares lessons learned from past crises to the global food system.

FOOD SYSTEMS GOVERNANCE FOR SYSTEMIC RESILIENCE

Governance plays a key role in regulating the dynamics of the global food system, mitigating risk and creating enabling conditions for positive transformation and change. (68) Given the multi-actor nature of the global food system in which diverse interests compete (45), effective governance to drive overall resilience is both extremely critical and challenging.

One compelling illustration of the existing challenges relates to the ownership and management of grain reserves – intended to buffer production shortages by stabilising food prices and protecting the population from food insecurity. However, since grain reserves are complicated and expensive to maintain, debates regarding their effective management remain ongoing. Even though state-owned, strategic reserves offer several benefits over reliance on private stocks, some governments and actors have advocated for private storage or monetary reserves instead (following a free-market approach and highlighting issues with weak governance and corruption in some countries). Private reserves, however, dramatically hinder resilience assessments and delivery of disaster aid. Being proprietary secrets, the amount of grains stored in private reserves is unknown to governments, hindering strategic planning and estimation of shock response options. (133, 134) Additionally, conflicting economic interests in times of shortages hinders timely release of the stored grains, encouraging price speculation. At the same time, countries most vulnerable to food insecurity are also the ones with the least resources to maintain state-owned stocks. (134) This has spurred calls for an internationally managed public grain reserve. (134, 135)

The grain reserve example draws attention to the resilience risks arising from private sector practices within the global food system. It also points to the need for effective regulation and global level coordination, as well as ongoing situation analysis to prevent and prepare for potential threats. However, there is no single international agency responsible for monitoring or providing guidance on enhancing the sustainability or resilience of the global food system. UN agencies such as the Food and Agriculture Organization (FAO) '*leads international efforts to defeat hunger*" and seeks to "*achieve food security for all*"[d], but does not involve global food system governance functions considering all sectors and outcome dimensions. The World

[d] See https://www.fao.org/about/about-fao/en/, accessed 8.11.2024.

Food Programme (WFP), in turn, is focused primarily on providing emergency relief and delivering food assistance, while stating 'building resilience' in its mission statement.[e]

Effective governance of the global food system requires a shared 'resilience vision' among stakeholders, ongoing negotiation of trade-offs and coordination of activities. Suitable strategies for food systems governance depend on what is being governed (natural resources, food products, food environments, private industry, trade, etc.) (68); geographic and temporal scales; the characteristics of administrative levels involved; and the impediments for implementation of measures, (24,99) As such, it is crucial that all actors effected agree on a shared vision and understanding of resilience and coordinate their actions accordingly to avoid duplication of efforts, to align activities and to fully exploit synergies and positive reinforcement. (45) This can be achieved only through a global level structure with broad stakeholder representation. As articulated by Fanzo et al. (2021), global governance driving positive food system transformation is 'the mode of interaction among the public sector, private sector, civil society, and consumers to identify, implement, resource, and monitor solutions for achieving healthy, sustainable, resilient, just, and equitable food systems without leaving anyone behind.' (24) Crucially, such arrangements can also provide a strengthened policy ownership and voice to LMIC and populations most direly affected by the current, negative food system outcomes – in line with the principles enshrined in the 2005 Paris Agreement on Aid Effectiveness and the 2011 Busan Partnership for Effective Development Cooperation.

New processes and structure(s) of global food system governance can also drive enhanced policy practice that adopts a holistic, full systems perspective and pursues collaborative approaches to solutions that enhance resilience of the whole system while avoiding isolated action with potential negative side-effects. Termeer, et al. (2018) propose a set of principles for such holistic policy action, which could be effectively furthered by a global food system governance body: 1) system-based problem framing, 2) enhancing connectivity across different governance structures including non-state actors, 3) having adaptability to respond to uncertainties and volatility during implementation and planning, 4) inclusiveness of multiple interest groups and actors (ideally all) to enable support and legitimacy, and 5) transformative capacities to create conditions for structural change, which is at the same time the prerequisite for the other four principles. (99)

Bolstering systemic resilience necessitates a global systems perspective coupled with considerations for the specific cultural, social, and political context of each country and region, as well as distal interactions and feedback effects between actors. Actors who have agency and influence may vary greatly and it is essential to understand their relationships and interactions to effectively navigate and shape the policy environment. (6, 68, 136) By incorporating diverse stakeholders operating at and across different scales of the global food system including representation of marginalised and highly vulnerable groups, a global multistakeholder body can facilitate the co-creation and alignment of global and national policy interventions and strengthen the incorporation of context-specific insights (including those on actor dynamics). At the same time, a multistakeholder structure would allow such a body to make choices between conflicting policy objectives. In order to reach financially, socially and politically sustainable and legitimate policy decisions, mere optimisation exercises are not sufficient: trade-offs and potential unwanted consequences need to be communicated and agreed upon by effected populations and relevant stakeholders. (90)

[e] See https://www.wfp.org/who-we-are, accessed 15.11.2024.

Furthermore, a dedicated governance body could be designed to strengthen the quality of resilience-building interventions and provide policy recommendations that address current caveats. For instance, there is limited understanding among policy practitioners on how to quantify the effectiveness of different policy interventions. This is partially due to the emphasis on process evaluation and monitoring (through Key Performance Indicators, for instance), instead of on methods for holistically evaluating the effectiveness and diverse impacts of adopted policy interventions. (68, 79) As extant literature underscores, monitoring the influence on food systems outcomes and identifying unwanted consequences should already be key elements in the policy implementation phase, to enable iterative and reflexive policy responses that can adjust as new information becomes available. (26,90,99) Systematic and ongoing impact evaluations are also desperately needed to better understand broader impacts and cause-effect relationships, such as those related to environmental variability and nutrition outcomes. (6)

Another key area requiring stronger standard-setting is that of equity considerations in resilience policies and interventions. Understanding how inequalities and power imbalances affect decision-making processes, and incorporating inequity considerations into policy design, implementation and evaluation, require strengthened mainstreaming. One example is the gender-responsive design and implementation of food system interventions. Women globally encounter distinct vulnerabilities, such as limited control over resources, heightened workloads in agriculture (especially during crises) and disproportionate share of onerous unpaid work. Women and girls absorb shocks personally to maintain the well-being of other household members and bear additional health and nutritional needs related to pregnancy and maternity. Hence, gender-responsive high-level strategies, and design and implementation of individual food system interventions are essential to avoid gendered negative impacts, and to exploit opportunities to further equity. (137)

SYSTEMIC RISK AND INTERVENTIONS – A THEORETICAL PERSPECTIVE: INTRODUCING THE SAFE AND JUST DECISION CORRIDOR

The resilience of the food system is not a mere outcome of the system but relates to its capacities to react to shocks and the decision space of actors to mitigate negative and enhance positive consequences. (35) The Safe and Just Decision Corridor (SJDC), presented in Figure 4, is a concept developed by one of the authors of this report (Estelle Paulus), which aims to inform consideration of different possible intervention pathways to build resilience within the food system and prevent social, environmental, or economic loss and damage, while avoiding waste of resources or accepting unnecessary trade-offs due to overadaptation.[f] While the Doughnut concept introduced earlier offers a relevant indicator tool, the SJDC constitutes a graphic to better aid consideration and highlight the timely dimension of action and to explain how inaction can restrict possibilities for interventions to build systemic resilience in the future.

[f] Overadaptation here refers to a situation where the cost of implementing resilience measures goes beyond what is considered justifiable (e.g. a high-cost measure applied to avoid an unlikely scenario) and might divert resources from more important measures or decrease resilience to other types of risks . Hence, overadaptation should be avoided for effective management of limited resources.

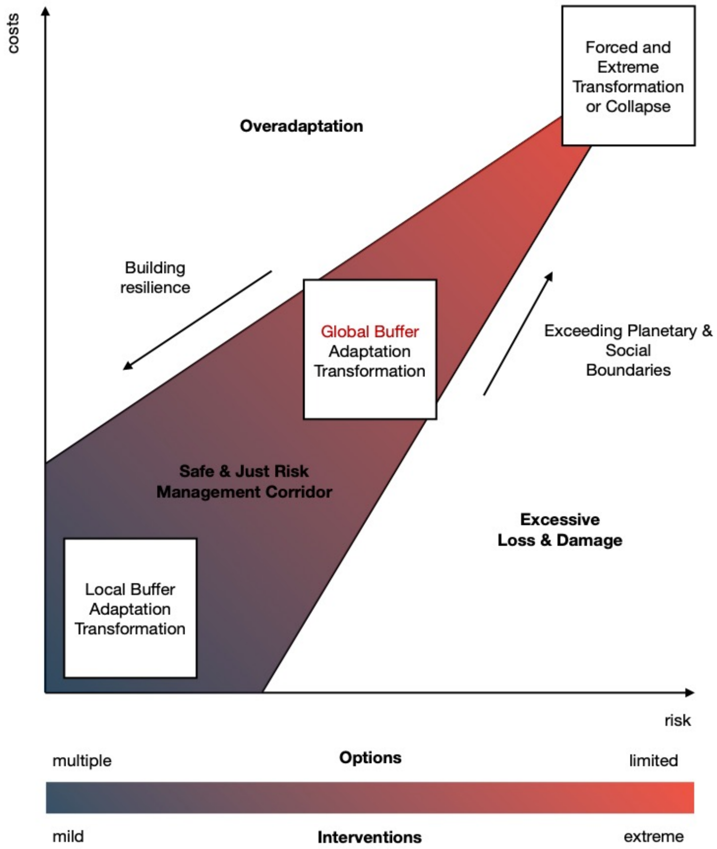

Figure 4: Sufficient measures for avoiding and managing systemic risks are located within the Safe and Just Decision Corridor (SJDC) and depend on the probability of systemic risk realisation. With increasing risk the SJDC shrinks, limiting available measures. When the risk of systemic collapse is low, absorption, adaptation and transformation opportunities are possible. In high-risk scenarios, transformation is the only and inevitable option. As risk increases, measures needed to prevent excessive loss and damage become more extreme and related costs increase (most likely non-linearly). While crossing planetary and social boundaries increases risks and drives up costs, restricting the SJDC further, building systemic resilience early and in a coordinated manner will prevent exploding costs and losses in the long run.

The further the global food system moves out of the 'safe and just' space of the Doughnut (2), and the longer the crossing of planetary boundaries and social foundations persist, the greater are the stress levels associated with the corresponding dimensions. Increased stress levels and higher likelihood of disruption, however, limit the possibilities for shifting the systems towards greater sustainability and resilience. This is highlighted by considering the impacts of climate change. With around 30% of global greenhouse gas emissions coming from the food system (138), the longer humanity waits to act to reduce the pressures of the food system on the climate, the more the food system will need to adapt to an increasing number of extreme weather events and shifts in local climatic conditions. This restricts the range of intervention options which may be sufficient to prepare for those risks. With greater frequency and extent of extreme weather events (e.g. droughts), buffer capacities (such as grain storage) or simple adaptation (such as switching the sourcing of products to a different region) might not be enough to limit the impacts on people (especially if vulnerability and inequality are already high and social boundaries are crossed). Crossing critical tipping points, such as a collapse of the Atlantic meridional overturning circulation (which might occur mid-century under current emission scenarios) (139) leading to changes to global atmospheric circulation (140), will have drastic consequences for local climate and ecosystems. This would lead to a forced and irreversible transformation of global food production and a potential breakdown of the system. A food system that stays within planetary boundaries and meets social foundations might be costly to realise in the short-term, but timely intervention is vital to avoid more drastic changes and greater costs in the near future.

As elucidated by Béné et al. (2016), the resilience of the food system is not a mere outcome of the system but relates to its capacities to react to shocks and the decision space of actors to mitigate negative and enhance positive consequences. Feasible reactions to shocks, as well as the probability that shocks develop into a systemic threat, depend on the duration and intensity of the shock, combined with emergent resilience capacities and the level of stress the system was exposed to before disturbance. Additionally, responses and adaptation strategies of affected actors can further amplify or limit the effect of a shock and have a major influence on whether the system enters the systemic risk zone, which is not represented here. (35)

The extent to which absorption, adaptation and transformation capacities are applicable varies across relative shock scenarios. (35) In general, the greater the extent and the duration of the shock to the food system is, the more likely it is that absorption capacities are insufficient and that adaptative interventions will be ineffective in mitigating the consequences of the risk. In very high risk scenarios, as more costly and extreme measures need to be taken, this culminates in a forced and radical transformation. That said, as highlighted earlier, small-scale disruption can also open windows of opportunity for change and can be, if exploited astutely, profitable for the system in the long run. (20)

Short shocks with low to medium severeness, paired with low stress levels and high buffer capacities, allow the food system to maintain its current activities simply by absorbing the effects of the disruption. Examples of such buffer capacities (grey and red lines, Figure 5) include national grain storage facilities or risk pooling through trade diversification which can buffer acute food shortages and local price spikes. In this case, no systemic risk arises (Figure 5, upper left). However, resource depletion due to reliance on buffer capacities will result in (temporary) higher stress level associated with higher vulnerability to further shocks while buffer capacities are depleted. Adaptive or transformational responses (e.g. investing in more resilient agricultural production through improved irrigation or switching to more sustainable practices) might require more time but can transition the system into a less stressed state in the longer term (green and blue lines, Figure 5).

Mild, but persistent disruptions, which can be slow onset (e.g. increasing water stress, etc.) or fast onset (e.g. the introduction of an adverse agricultural policy) are not effectively addressed by buffer capacities. This is because buffer capacities (e.g., using lakes or reservoirs as an additional water supply in case of decreasing annual rainfall) will continue to be depleted over time. Relying only on absorption will result in a permanently higher stress level of the food system, bringing it closer to the ‘systemic risk zone’ and making it more vulnerable to future shocks (Figure 5, lower left).

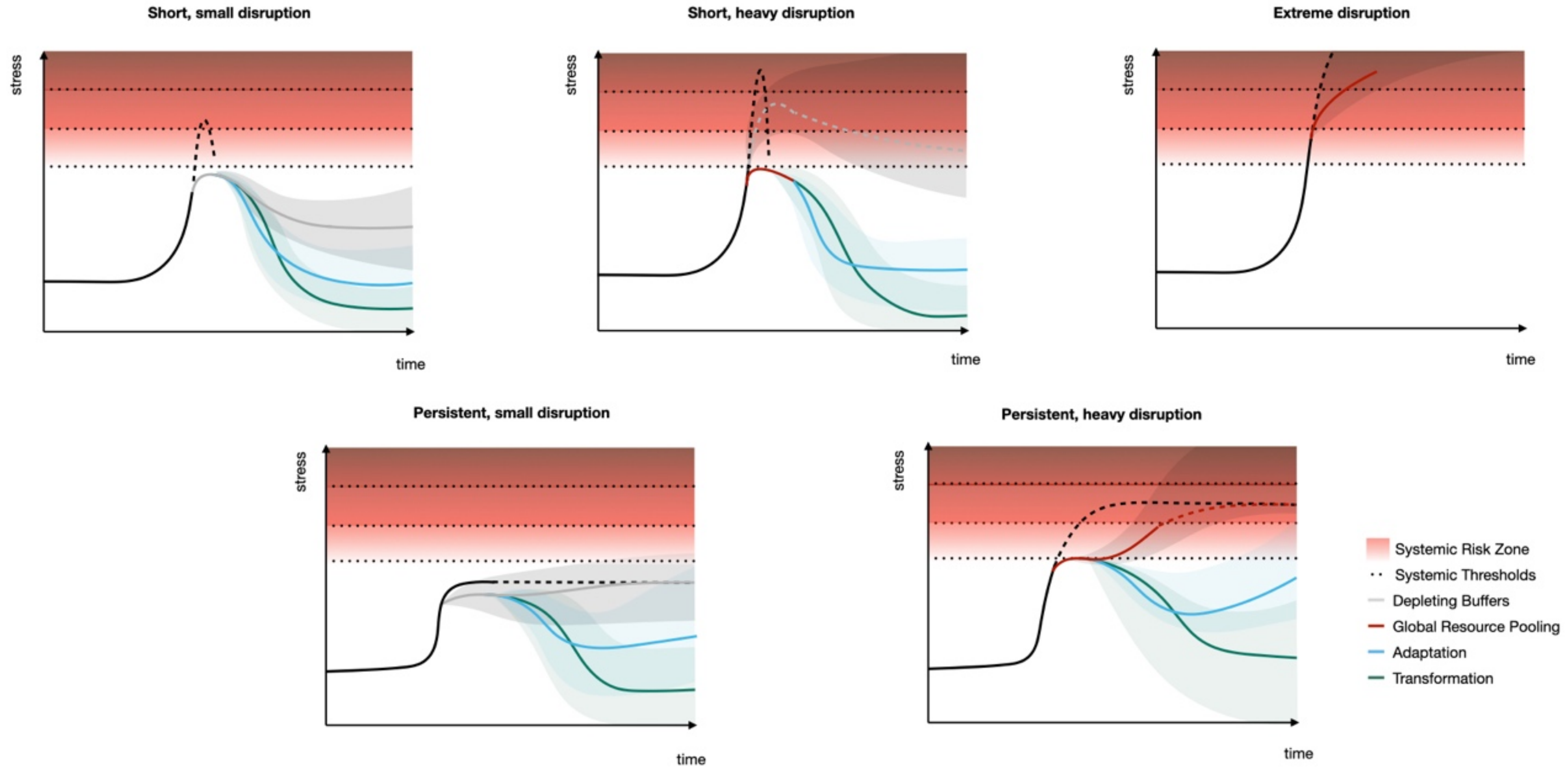

Figure 5: Decision space for different shock scenarios visualising effectiveness of buffer (grey), adaptive (blue) and transformative (green) capacities of the system. Global buffer capacities (dark red line) include internationally coordinated capacities which are external to the food system, specifically designed to prevent realisation of systemic risk cases. However, buffer capacities (local and global) present a short time relief for shocks but will be depleted with ongoing disruption. With increasing extent of the shock, the risk of crossing thresholds for tipping points and entering the zone of self-reinforcing risk cascades ('the systemic risk zone' increases dotted lines, shades of red) is increased . In this zone total collapse or irreversible consequences can no longer be avoided.

Heavy but short shocks might exceed the internal buffer capacities of food system actors and require the system to change its internal interactions to adapt to the new situation in the long run (Figure 5, upper middle). As an example, if a certain region is affected by a production shock, importers may draw on redundancy within the global supply and switch from one exporting country to another. This ability to adapt will help to limit the spread of the shock and avoid cascades, so that no systemic risk arises. However, adaptive and transformational measures might be too slow or insufficient to cope with the first direct effect of the shock, in which case buffer capacities will also be needed. External, 'global buffer capacities' designed for cases of extreme disruption and released when triggered by an event can prevent the system from entering the systemic risk zone (e.g. international budgetary support for low-income countries to sustain temporary subsidies to cap price spikes for the domestic population).

Strong disruptions with long, or unlimited duration (e.g. changes to agricultural conditions due to compounding effects such as water scarcity plus rising temperatures) will require the system to change its behaviour completely (locally or globally) to avoid increasing systemic risk. Here, global buffer measures can play a role in risk reduction, but only as a transitional measure to enhance fast change. Being costly to maintain and relying on good international cooperation during a crisis, such measures can only provide a short-term solution, as they introduce new stress on resources which endangers resilience in the long run. (32) Moreover, in the face of persistent disruption, internal adaptive capacities may prove inadequate for long-term stress reduction, especially when resilience factors like redundancy are also diminished by the disruption. Hence, in this case, transformation is key to stabilising the system and defining the path to more sustainability. However, implementing measures for change ex-post shock occurrence is likely to be more costly and time-consuming than ex-ante, given that these actions must manage both the costs of change and the heightened stress on the system simultaneously (Figure 5, lower right).

Intense shocks will surpass the food system's ability to adapt or self-organise (Figure 5, upper right). Systemic collapse might be inevitable, at least temporarily. That is to say, even potentially expensive global measures may prove insufficient to prevent the system from collapsing into an undesirable state, leading to a failure to meet one or more of its intended outcomes on large scale. Transformation into a new state is now forced and determined by the failure, with high costs to mitigate damage and adapt to the new state, and limited options for decisions aimed at re-establishing desirable properties of the food system.

For more severe and persistent disruptions, the ability of the food system to adapt through internal reorganization is more and more limited and cascading shocks become more likely (Figure 4). For example, if a supply shock affects a lot of production regions simultaneously, or if the affected supplier was dominating the market leading to low redundancy capacity in the system, the shock could result in direct supply shortages or indirect supply difficulties (for example, related to price spikes) making the production of downstream products impossible, or nonprofitable. (13)

Overall, more severe shocks of longer duration restrict policy and societal response options for reducing impacts and mitigating further risks in the future. As illustrated by the SJDC concept, as risks increase, the necessity for transformation becomes more compelling, and the associated measures become more expensive, both in terms the cost of required actions and potential losses and damages resulting from undesired changes in the system (Figure 4).

Moreover, cost-risk relationships might increase non-linearly when entering the systemic risk zone, due to the increasingly drastic measures needed to sustain the functioning of the system. Loss and damage as risks are realised might include impacts on human lives (death and disease due to malnutrition), the environment (climate and ecosystems), the global economy and social welfare (increases in poverty, threatened livelihoods, cultural values, and inheritance). At the same time, it is important to consider whether applying costly measures to avoid specific risk scenarios with low probabilities will divert resources away from other interventions to increase resilience. Therefore, careful consideration of suitability and proportionality should accompany intervention design and implementation.

Lastly, even though adaptation and transformation are presented here as positive strategies for building resilience and decreasing risk likelihood, it should be noted that if coordination and a vision for long-term resilience are missing, adopted measures may generate negative outcomes if they fail to consider the resilience of all parts of the system. (35,45)

INTERVENTIONS TO BUILD SYSTEMIC RESILIENCE WITHIN THE FOOD SYSTEM

Policy interventions in the context of global food systems governance can be roughly categorized into regulatory instruments, market interventions, informational instruments (also called soft measures), voluntary agreements and organisational instruments (see Table 4 for examples). Regulations include instruments of planning, enforcing, and assessing thresholds, standards, decrees, and prohibitions, such as conservation laws. Market interventions can include positive incentives such as subsidies or payments, negative incentives such as taxes or penalties, redistribution incentives (e.g. fiscal transfer, off-set, and banking), and the definition of ownership rights. Here, we categorise voluntary agreements as soft measures, alongside persuasive measures (such as public education or promotion of ethical behaviour) and early warning systems that guide intrinsic motivation. However, in practice, measures summarised within one category might vary greatly and overlap with other interventions. (141)

Based on a holistic systems approach, packages of interventions and innovations combining prevention and mitigation measures should be designed, assessed, and implemented to build *systemic* resilience, as uncoordinated individual measures will not be sufficient. (32,66) For the design, implementation and evaluation of policy strategies, comprehensive multi-dimensional and preferably multi-scale tools – such as the Sustainability Compass or the Doughnut framework – should be deployed to identify the trade-offs, synergies and unwanted consequences associated with different interventions and associated outcomes, and to enable multi-stakeholder collaboration. (90)

Moreover, preparing narrowly against specific threats (e.g. avoiding reoccurrence after a specific event was realised) is not sufficient to avoid catastrophic impacts in the future, due to the unpredictability and uncertainty associated with future shocks. (142, 143) Instead, it is important to enhance resilience capacities, which will provide the system with ability to reduce the likelihood of risk spread (e.g. enhancing diversity and redundancy) and enhance the action space of affected actors to react to a diverse set of possible shocks. Furthermore, particular attention should be paid to the potential coincidence and mutually reinforcing effects of different shocks and stressors, leading to compounding risks. More research, frameworks and data are needed to develop policy recommendations that prepare our food systems for a ‘perfect storm’ of coincident events. (66)

Table 4 below presents a non-exhaustive list of different recommended policy interventions to drive global food system resilience. Policy interventions can be classified depending on whether they address the food system indirectly by targeting a driver or directly by influencing its actors. For example, interventions to limit climate change, which is both a constant stressor (e.g. causing water scarcity or increases in temperature above tolerable thresholds), and a source of increasingly severe disruption to production and trade (through the increasing probability of extreme weather events), might not be tailored towards the food system, but can still have a significant effect on reducing systemic risk. (144) A study by Gaupp et al. (2019) finds 'that limiting global warming to 1.5°C would avoid production losses of up to 2753 million (161,000, 265,000) tonnes maize (wheat, soybean) in the global breadbaskets and would reduce the risk of simultaneous crop failure by 26%, 28% and 19% respectively.' (130)

If effectively implemented, interventions designed to sustain ecosystem services (protecting and restoring biodiversity, degraded terrestrial and aquatic systems, etc.) – such as the 30 x 30 deal (145), can change the institutional setup and governance of food systems at different spatial scales, shape the economic, social, or fiscal situation of actors (e.g. institutions supporting biodiversity giving resources to farmers to protect and restore nature) or impact production, supply chains, consumption and waste directly (e.g. by banning certain pesticides).

Furthermore, resilience-building interventions can follow different strategies. Firstly, they can buffer the effect of a shock after occurrence (sometimes referred to as resilience by intervention). Secondly, they can enhance the preparedness of actors by monitoring and forecasting possible trigger events and related risks. Thirdly, they can decrease the probability of shock occurrence directly (e.g. changing unsustainable practices in agriculture). Lastly, they can prevent risk cascades and absorb future shocks indirectly, by building resilience capacities, limiting stressors, or enhancing the ability of the food system to self-organise (for adaptation or transformation). Measures increasing resilience through planning and monitoring of long-term change, in contrast to event-triggered buffering measures, are sometimes referred to as resilience by design. (32)

Interventions act on different temporal scales, in terms of time needed for implementation, whether the aim is for primarily short- or long-term consequences, and whether they address systemic risks pre- or post-disaster (here, referred to as ex-ante, or event-triggered measures). As short-term, post-disaster adaptation measures are competing with longer-term ex-ante measures for resources and implementation priority, synergies and inevitable trade-offs should be identified and considered carefully. Adequately targeted and internationally coordinated short-term measures (12) are key to preventing further cascading effects following a disruption.

Table 4: Typology of possible interventions for building systemic resilience (as suggested in the literature). This table is intended to provide examples and is not a comprehensive overview of all possible interventions. Ex-ante interventions which are directly affecting the systemic resilience of the food system are presented in dark blue, while direct event-triggered interventions are presented in orange, with global buffers in red. Indirect interventions, which are exclusively ex-ante, are presented in light blue. Interventions which can influence different response strategies are listed multiple times.

Type	Shock Prevention	Shock absorption	Preparedness	Stress reduction
Regulations	Self-sufficiency targets for national food systems Maintaining asynchrony and diversity between areas of food producing and sourcing Landscape planning for agriculture Strengthening and protecting soil health Strengthen food safety standards Trade barriers (to avoid pest/disease spreading) Intergovernmental risk pooling between breadbaskets Avoiding short-term responses that hinder long-term sustainability and resilience (e.g. transforming environmentally protected lands into production). Developing conditional trade regulations under systemic risk (trading rewards for refraining from imposing export restrictions)	Increasing resilience standards for infrastructure Requesting grain-trading partners to store grain in destination markets Globally organised and managed rain storage and reserves Intergovernmental risk pooling between breadbaskets	Creating a global food system resilience agency for monitoring and consultancy Introducing ongoing monitoring of chokepoint congestion and failures Design and implementation of rapid reaction plans for action (based on shock scenarios)	Assess, restructure and remove inefficient subsidies Technical and financial support to smallholder farmers (poverty alleviation, transition into more secure livelihoods) Systematic reduction of food waste along supply chains Waste management (reducing pollution) Creating a global food system resilience agency for monitoring and consultancy
	Antitrust regulations Financial stress testing & banking regulations Introducing public sector performance contracts evaluated by citizens (example: Imihigo contracts in Rwanda)			Environmental impact assessments for companies Environmental provisions and performance criteria in bi-and multilateral trade agreements Progressive carbon takeback obligation

				Stopping deforestation and limiting land use change Systematic reduction of food waste in supply chains (e.g. improving cooling, etc.) Adopt biodiversity and ecosystem conservation targets Including natural capital considerations in decision-making processes Natural resource management standards for agriculture Protected areas and nature restoration Establishing multilevel-coordination bodies to ensure effective implementation of policies Introducing public sector performance contracts evaluated by citizens (example: Imihigo contracts in Rwanda)
Market Interventions	Systemic risk tax for companies Incentives for diversification of production Incentives to shift to more resistant crops (weather, pests) Investment in storage infrastructure Investment in more resilient trading infrastructure (ports, roads, etc.) Avoiding sanctions and export restrictions that obstruct food and fertilizer trade	Investment in storage infrastructure Non-parametric systemic risk insurance Price controls for certain food stuffs Avoiding panic buying or hoarding to increase national stocks International budgetary support for LICs to sustain (temporary) subsidies Market controls: conserve grain stocks for human consumption	Incentives to shift to more resistant crops (for example against drought or common pests) Investment into more resilient trading infrastructure (ports, roads, etc.) Investment in storage infrastructure	Asses, restructure and remove inefficient subsidies Technical and financial support for smallholder farmers (poverty alleviation, transition into more secure livelihoods, e.g. diversifying their sources of income through on-farm-processing or diversification of products) Investment in early warning systems for production (pests, market fluctuations, extreme weathers, etc.) and facilitating monitoring of risks Investment in primary processing at farm level (reduce pre-farmgate food loss and contamination)

		Subsidies for farmers to limit the influence of higher input (fertilizer) and energy prices Avoid sanctions and export restrictions that obstruct food and fertilizer trade		Invest in global monitoring of spatial patterns in crop production to identify best producing areas, including sustainability analysis Investments in Agroforestry and Agroecology Debt relief for poor and food-insecure countries Revisit and reduce subsidies and mandates for biofuel production to avoid competition with human food production
	Investment in research to identify optimal policies, programs and interventions (incentivise collaboration between natural and social sciences) Subsidies for funding of technological development and innovation Fund building of food system capacities and transformational processes from tax revenue (to make financing sustainable)		Expand benefits, reach and duration of social safety nets Fund building of food system capacities and transformational processes from tax revenue (to make financing sustainable) Investment in research to identify optimal policies, programs and interventions (incentivise collaboration between natural and social sciences) Subsidies for funding of technological development and innovation Expanding telecommunication infrastructure (for early warning, mobile banking, and information transmission)	CO_2 tax Emission certificates Addressing current humanitarian need (through funding for programs and organisations) Reallocating subsidies towards public instead of private goods Subsidies for sustainable agriculture Investments in Agroforestry and Agroecology Payments to actors for protecting and restoring ecosystem services Allocating human resources for the implementation and monitoring of policies Expanding telecommunication infrastructure (for early warning, mobile banking and information transmission) Investments in remote sensing and data (for producers and research; identify optimal levels of inputs) Subsidies for technological development and innovation funding

Soft Measures	Incentives for the breeding and cultivation of livestock and crops with diverse genetic background Protecting diversity, by keeping traditional and locally adopted crops and avoiding replacement by wheat and maize Investing in analyses of how local production can be sustainably and cost-effectively raised to become more self-sustained Establishing multi-stakeholder platforms for designing food system transformation schemes (including representatives from private sector, civil society, and policymakers, meeting at regular intervals)	Enabling effective coordination between disaster response actors (national & local governments, agencies, and stakeholders) and processes	Join and coordinate global, national, and regional initiatives to build resilience Country-specific analyses of food security risks (price shocks, trade restrictions) Real-time monitoring of food and input price volatility Establishing a taskforce on climate-compatible infrastructure Global vulnerability mapping for population at risk of hunger Sharing of knowledge and lessons learned from the realisation of chokepoint risks and their management Forecasting of Climate Oscillations Identification of critical food security corridors in global trade Tracking plant pathogens and pests across borders (Genomics) Setup of infrastructure committees which capture risks on major infrastructure failure Undertake assessment of exposure and vulnerability to chokepoint risks (for major importer countries)	Establishing a taskforce on climate-compatible infrastructure Establishing multi-stakeholder platforms for designing food system transformation schemes (including representatives from private sector, civil society, and policymakers, meeting at regular intervals) Joining and coordinating global, national, and regional economic initiatives to build resilience Promoting healthy and environmentally sustainable diets Promoting sustainable farm models
	Developing comparative performance metrics for monitoring and evaluation of implementation of policies Strengthening international relations and peace		Facilitating technology and knowledge transfer	Communication to affected populations and local policy makers to improve water, sanitation, and hygiene practices

	Facilitating technology and knowledge transfer			Development of comparative performance metrics for the monitoring and evaluation of policy implementation Introducing community scorecards where citizens independently monitor and report public and private sector performance on agreed commitments (examples: Ghana, Rwanda) Strengthening international relations and peace

INSIGHTS FROM POLICIES IN PLACE AND LESSONS LEARNED FROM PAST CRISES

Despite the rapidly changing challenges of an ever-evolving food system under increasing pressure from climate change and environmental degradation, past crises offer the chance to understand the impacts of short-term policy responses and disaster aid previously implemented by countries and international organisations.

Past crises highlight the fact that the global food system, being optimized for cost efficiency and gains for major actors, is currently not configured to absorb or reduce exposure to systemic risks. In contrast, it exhibits systemic properties which make it more susceptible to self-propagation of shocks (9), and endanger its long-term functioning through unsustainable behaviour. (8) It is not sufficiently diversified (both in terms of products and geographic space) (9), relies on few global chokepoints (e.g. production hotspots, high economic concentration of few companies dominating the market for certain products, or trade chokepoints such as major ports) which increases systemic vulnerability to shocks (76), and exhibits persisting inefficiencies, inequities between countries and regions, and uneven distribution amongst countries and within populations leaving billions vulnerable to shocks. (20)

During food production or price crisis, countries often react by imposing export bans, restrictions, quotas, or higher taxes on food and fertilizer products – as seen in the 1970 oil crisis, the 2007–2008 food crisis, in 2010 during the drought and wildfires in Russia, and more recently in response to the war in Ukraine. (9, 12, 15, 66, 78) However, such measures lead to a supply shock for importing countries, affecting food availability of local populations, as well as production and processing of food since important inputs are missing. (13) These cascading risks highlight the need for more regulatory arrangements on export restrictions (12,16,146), while recognising national governments' priorities to protect domestic food supply and markets in times of crisis. (9) Another lesson learned from crisis situations is the pressing need to strengthen self-sufficiency (6, 78) and grain storage within importing countries. (9, 125)

Furthermore, the preceding decline in grain storage was identified as one of the long-term drivers for the surge in food prices in 2008. (133, 147) Besides the negative effect on food security through impacts of direct accessibility (i.e. buffering production shocks) (125) and related price buffering capacities, reduced stocks drive food price speculation. (148) Therefore, building and securing stocks at the country level is vital for limiting ripple effects arising from production shocks, trade disruptions or price spikes. (125, 133, 147, 149) Additionally, it is crucial to determine the ownership of stocks, to ensure that governments possess comprehensive information on stocks and to establish regulatory frameworks for the timely release of stocks during critical periods to curb price speculation. Additional research is needed to better understand the implications of privately owned reserves (held by companies and, to some extent, consumers) for resilience. (133) Furthermore, as seen in the past, when faced with an acute crisis, countries must avoid hoarding and panic buying, which worsen global shortages of specific food items and amplify price spikes. (9, 12, 147)

Additionally, policies on tax credits, tariffs and mandates for biofuel are believed to increase prices of globally important crops such as maize, rice, corn, and wheat, and were identified to be one of the main drivers of the 2008 global food crisis. (12,147,150) Removing such subsidies and policy-induced growth is, therefore, a lever for decreasing the pressure on agricultural commodity markets and increasing food availability and affordability. (12,137,146)

Furthermore, food crises have the potential to delay the required transformation of the food system towards a more sustainable future, endangering resilience building and restricting the Safe and Just Decision Corridor (SJDC). For example, Russia's war in Ukraine has led the European Union to postpone its transition towards a greener infrastructure (delaying the publishing of sustainable farming recommendation, 'Farm to Fork' strategy, etc). (11) However, delaying the transition fails not only to release the system from stress but intensifies the risk of future shocks (caused by extended biodiversity loss and/or climate change).

A policy brief by the CGIAR Group (2022) on limiting the impacts of crises on global food security emphasises the need for clearly targeted short-term responses (avoiding general instruments like tax reductions). (12) Additionally, the authors put forth two main strategies for event-triggered interventions to build back better and enhance long-term food production and resilience. Firstly, they point to the importance of risk monitoring and early warning systems, to enable fast and effective responses. One example is the Anti-Locust Invasion Centre in Madagascar in 2014, which helped control locust outbreaks and lower food production decline. Secondly, the authors suggests that efforts to mitigate the effects of a current crisis should be paired with interventions to build resilience in the long run (e.g. the Public Employment for Sustainable Agriculture and Water Management Project in Tajikistan, 2010). (151)

Even though crises like the Ukraine war are disproportionally affecting the world's poor (11–13,15), they also shed light on vulnerabilities and inefficiencies within the highly specialised and interdependent food systems in richer countries. Poverty and income loss, combined with more specific properties of the COVID-19 pandemic (lockdown measures and physical distancing measures), have revealed regulatory inefficiencies and inequality of distribution. Despite poorer populations struggling with food supply due to rising poverty and income loss (including in HIC where food deserts and reliance on food banks and school meals are growing phenomena), over- and mis-supply (e.g. intensified food loss in the US market during lock-downs, where the organisational structure made it nearly impossible to redirect food produced for restaurants to grocery stores) led to increases in loss and waste. (8) In more resilient food systems such inefficiencies need to be avoided.

The COVID-19 pandemic has also revealed other vulnerabilities within the extant food system. Highly specialised supply chains and reliance on a few major processors caused chokepoint risks, as seen with the bottleneck effects of shutdowns of large processing plants on meat supply in the US and Europe in 2020. (8) In a similar vein, existing literature drawing on network analysis suggests that food systems are highly fragile if key components are stressed or fail. (9) Further work is needed to better understand concentration risks versus the potential advantages for efficiency and cost of greater specialisation in the food system.

Moreover, the closing of borders within Europe, to stop the spread of the coronavirus, highlighted the dependency on migrant and seasonal labour imported from other countries (8), rendering food systems susceptible to political shocks and pandemics. Self-sufficiency of countries, hence, extends beyond mere food supply and should be considered more broadly. (6)

Lastly, due to the complexity of food systems, increase in global trade, consumption of processed and multi-ingredient food products, as well as increases in food prices, consumers have only limited options to exercise control over their diet's influence on environmental and climate risk. (6) This underscores the limitations of relying on consumer choices (e.g. favouring organic or locally produced products) to pursue sustainable food transformation and mitigate exposure to environmental or economic shocks. Instead, effective policy making is needed to address these issues on global scale.

All in all, past crises have highlighted the need for more internationally coordinated action in case of global crises to avoid severe impacts, especially on the world's poorest. Furthermore, reduction of existing vulnerabilities, alongside the introduction and strengthening of resilience capacities are needed to avoid repeating mistakes made in the past.

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