Systemic risk and food security. Emerging trends and future avenues for research

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Abstract. The unanticipated international food price spike of 2008 has raised concerns about global food security. Might food systems lastingly fail to supply, trade, and distribute food? Might widespread unsustainable agricultural practices irreversibly alter ecosystems? Or might large scale food shortages trigger political unrest? To answer these questions, we reflect upon the concept of systemic risk and conduct a review of the literature on systemic risks and food security. First, we present the concept of systemic risk and current trends in systemic risk research. We then analyze contributions on systemic risk and food security. We first show that the literature has so far focused on a) agricultural production and correlated yield-losses, and on ways of pooling risk at regional or global-level, and b) the role of international trade in increasing or decreasing systemic risk. We then identify avenues for further research, highlighting the impact of intensive farming on ecosystems. Finally, we discuss the concept of systemic risk: we show that scholars need to be careful when assuming that there exists just one global food system; we show that systemic risk can be understood in various ways, beyond the domino effect paradigm.

Introduction

The issue of systemic risks to food security has grown rapidly in recent years, both in research and in international institutions (Gaupp et al., 2017; Liu et al., 2017; Puma et al., 2015; Sartori and Schiavo, 2015). The 2008 food crisis in particular acted as a wake-up call for researchers and the international community regarding the vulnerability of food systems, the potential for new kinds of food crisis and the political consequences of such crises (Beddington, 2009; Godfray et al., 2010). Concerns have arisen about the future of food and agriculture and the various risks affecting food security, involving processes of continuous change and extreme events (Davis et al., 2021). Interest in the notion of systemic risk is in fact related to several concerns: (1) the growing complexity of food systems linked to globalization, involving new interdependencies (and dependencies) and related risks, well beyond production alone; (2) climate change and its consequences for agriculture; (3) the sustainability of food systems (maintaining primary resources, limiting the negative impact of production and food on ecosystems); (4) global demography (population growth, urbanization, diet change).

The notion of systemic risk captures all of these changes in a global fashion. It reflects the idea that the growing complexity of food systems, the multiplicity of and the interactions between risks, and the interdependence between social and ecosystem transformations create new vulnerabilities and make possible systemic crises (Davis et al., 2021). It also relates to the inadequacy of existing public policy frameworks to cope with these crises. An understanding of the underlying mechanisms of such systemic risks is therefore required, especially for the purposes of public policy transformation, in order to prevent systemic crises from occurring.

Risks affecting a single individual or organization are usually regarded as being independent of risks that affect other individuals or organizations and can be managed through individual protection, prevention and insurance mechanisms. Systemic risk, on the other hand, refers to a risk which, due to the interdependencies between the components of a system, simultaneously affects all actors or components of a system, thus thwarting conventional measures such as risk pooling or risk diversification. Particularly used in finance (Billio et al., 2012; Brunnermeier and Oehmke, 2012; de Bandt and Hartmann, 2000), where powerful interdependencies between actors have existed for some considerable time, the idea of systemic risk helps to understand and prevent large-scale crises where all the elements of the system fail simultaneously and where self-sustaining or self-propagating mechanisms operate (precisely because of these interdependencies). In the case of finance, the anticipation of systemic crises leads to the adoption of specific measures which might be deemed unnecessary or harmful under an efficient market hypothesis.

Yet as is often the case when a term becomes widely used (Brouwer et al., 2020), and because systemic risk encompasses a wide range of concerns in the field of food security, there is a great deal of confusion about the meaning and use of the term. Categorizing everything as a 'systemic risk' can obscure as much as it illuminates the phenomena and mechanisms at work. First of all, there is no consensus on the mechanisms (exogenous or endogenous) underpinning systemic risk: different models compete with one another, leading to completely different views of the problem and of possible solutions. The explanatory models must be specified: when we talk about systemic risk, are we talking about external shocks, or are we talking about a system's internal processes which favor the invisible accumulation of a load that eventually leads to the complete breakdown of the system (Homer-Dixon et al., 2015)? And can these different mechanisms interact? Secondly, are the interdependencies in the field of food of the same order (same strength) and nature as in finance? Financial interdependence is based on a pure exchange system. If the system ever runs short of liquidity, one can reasonably expect a lender of last resort to inject liquidity to save the market from disruption. Food, on the other hand, connects social and natural systems and relies on primary resources that cannot be injected into the system at will.

Finally, there is a public policy and regulatory issue. Systemic risk analysis recommends measures (e.g. redundancy, stocks, taxes) that would otherwise be seen as useless or harmful. It is therefore necessary to have a clear understanding of the measures and transformations that can limit systemic risk.

In the following we trace the genealogy of the concept of systemic risk, and propose an analytical framework, which distinguishes the nature of the interdependence (social or material) and the mechanisms (exogenous or endogenous) at work. Then we apply this framework to food security and conduct a literature review on systemic risks and food security. We show that the notion of systemic risk has been increasingly used to discuss the vulnerabilities resulting from international trade, but also to the issue of the irreversible transformation of ecosystems. Finally, we discuss the transformative scope of systemic risk approaches to food security. Just as there are competing interpretations and approaches to systemic risk, there are competing associated policy options: on the one hand, a "doomsday liberalism" that naturalizes trade liberalization and disasters while to some extent mitigating them, and on the other, a transformative vision that relies more on a change in ways of life and in the organization of production and exchange.

1. Systemic risk. Genealogy of a concept

Risk, in its most general meaning, is defined as the probability of occurrence of an adverse event, times its impact (Helbing, 2013). While there is no stabilized definition of systemic risk (Billio et al., 2012), the latter is commonly approached as the risk of a generalized failure or collapse of all the components of a system, as opposed to the individual risk of default of a single entity. A car accident, for example, corresponds to the conventional model of risk: the risk to one specific driver does not affect the risk incurred by all car owners. On the other hand, phenomena such as climatic accidents, epidemics or economic crises affect all agents simultaneously, independently of their individual risk-taking.

In order to take account of the uses of the notion of systemic risk and its disciplinary roots, we compiled and analyzed a corpus of 2,360 scientific publications[1]. While systemic risk is present in all types of field, the literature on this concept is mainly rooted in finance, due to the very strong interdependencies between the agents of this system (de Bandt and Hartmann, 2000). Experiences of global financial crises (from the 1929 crisis to the “subprime crisis” of 2008) have fed into the thinking on the risks of financial system collapse. Finance theory distinguishes between two ways of understanding systemic risk: endogenous and exogenous (Aglietta, 2003). This corresponds to two paradigms of systemic crisis: the *hurricane* and *domino* effects. An endogenous view of systemic risk is one where a systemic shock operates like a hurricane: just like an internal oscillation of the climate, it hits all actors from the word go and constitutes an aggregate shock from the outset. Conversely, in the exogenous vision of systemic risk, the crisis stems from an external shock (local or aggregate). This commonly relates to the imaginary of the domino effect: a localized shock or accident that subsequently spreads to all actors, because of their interdependency (domino effect). Not only do these two mechanisms put forward a different vision of the causes of disruption, they also differ in terms of the timeframe of the crisis: while the contagion paradigm focuses on short-term processes of disruption, the hurricane paradigm sheds light on the long-term causes and consequences of a systemic event. In finance it is the exogenous vision of systemic risk that dominates. As a consequence, financial economics is more interested in the effects of an exogenous shock on the financial system than in the way in which financial markets, through their own functioning, generate risks of the collapse of the entire financial system or even of the economy.

From a methodological point of view, the analysis of systemic risk has evolved considerably in recent years. In particular, since the financial crisis of 2007, it has benefited from the development of complex network modeling (Albert et al., 2000; Barabási and Albert, 1999; Newman, 2003; Watts and Strogatz, 1998). Scale-free networks, in particular, are centralized around a small number of hubs that collect the

[1] This corpus was obtained from a "systemic risk*" query in "Topic" (from 1956 to the present day) on the *Web of Scien*ce database. We used the Cortext platform to study this corpus.

majority of the links in the network, while the majority of the nodes have just a few links and are weakly connected to one other. Scale-free networks are considered to be both very efficient, due to their small size (Cohen and Havlin, 2003) (Cohen and Havlin, 2003) and highly vulnerable to targeted attacks, due to their centralization (Cohen et al., 2001, 2000).

Borrowing tools from physics, epidemiology and ecology, researchers and analysts have increasingly studied financial markets as networks, and have shown that these markets exhibit the characteristic properties of scale-free networks (Soramäki et al., 2007). Such an approach dramatically changes the analysis of financial risks and recommendations for governance. The tools for regulating financial risks are built on the assumptions of arbitrage pricing theory and assume that the more complex the exchanges (securitization, derivatives), the more diversified the risks. An analysis in terms of network topology shows that this analysis may be true only up to a certain point: beyond a certain threshold, an increase in complexity (i.e. in the number and diversity of transactions) generates instability that can threaten the system as a whole (Caccioli et al., 2009; Gai et al., 2011; Haldane and May, 2011; May et al., 2008).

After being adopted in finance, systemic risk analysis using complex system tools has spread to other social sciences. The notion of systemic risk (understood as a “networked risk” (Helbing, 2013) has become widely used to study issues defined as global, such as climate change, the environment, the economy or food (Centeno et al., 2015; Challinor et al., 2018; Renn et al., 2017). These studies assume that globalization goes hand in hand with widespread interconnectedness and interdependence. In this literature, global interconnectedness leads to a new type of risk, “global systemic risk”, which presupposes that the world henceforth constitutes a system within which contagion phenomena can rapidly impact the entire planet. Using the concept of systemic risk helps to characterize the new vulnerabilities that globalization brings about and the way in which we can manage or mitigate these vulnerabilities (Centeno et al., 2015).

Researchers characterize systemic risks in terms of *non-linear* cause-effect relationships, due to *positive feedback* effects between different components of the system - and thus between effects and causes. These characteristics of systemic risks are most often associated with a singular property: they lead to abrupt and irreversible shifts when thresholds are crossed for certain key parameters (“tipping points”). A system that has for a long time remained stable and robust in the face of multiple shocks or accidents may therefore suddenly become unstable, out of control and switch to a different state (Helbing, 2013) (Helbing, 2013). Once a tipping point is crossed, the structure of the effects of systemic risks is uncertain, in such a way that several stable states are made possible (Renn et al., 2017).

In the case of human systems, risks spread not only due to the structural features of a system, but also due to the perceptions, affects, feelings and reactions of individuals or organizations (Haldane and May, 2011). This is what some authors call "the social amplification of risk" (Challinor et al., 2018; Renn and Keil, 2008). All authors agree that when it comes to assessing and managing systemic risks, none of the existing regulations are fully suitable; they are designed to manage isolated risks and are thus ineffective for systemic risks. As far as risk management is concerned, risk taking that is considered acceptable from the individual risk regulation viewpoint may well contribute to increasing systemic risk. Helbing suggests adding a principle of collective responsibility to the principle of individual responsibility (Helbing, 2013). In terms of risk management, several contributions identify possible solutions (Helbing, 2013), such as: redundancy, compartmentalization (or system connectivity reduction), system size reduction, back-up system, automatic slowdown mechanisms and reserves (D'Odorico et al., 2018).

We have seen that systemic risk is the object of two competing approaches: an endogenous approach and an exogenous approach. But this distinction may be insufficient. In finance, the interdependence between the elements of a system can be defined through social interaction (in this case, market exchange). However, by taking up network models derived from ecology, finance researchers have removed the biophysical dimension of interdependence, which is very important in ecology. An ecosystem is defined not only by the interaction between various species (food web), but also by its biophysical status (e.g. soil quality, water resources, biodiversity level) and governing ecological processes which affect its productivity and resilience. It is therefore necessary to add a second distinction, relating not to the mechanism of risk propagation, but to the nature of the interdependence in the system: social interaction or a biophysical property. This dual characterization of systemic risk can be summarized using the following diagram (Figure 1):

Figure 1

Systemic risks can be classified along two dimensions: the nature of the interdependence (horizontal axis, shared biophysical properties/interaction) and the mechanism of risk (vertical axis, endogenous/exogenous). Examples of systemic risk are given for each case: food security in red, other areas in black.

2. Systemic risks and food security

In this section, we focus on the relationship between food security and systemic risks. We will first consider systemic risks to food security; then we will look at food security as a cause of systemic risk (for other systems). In order to gain intelligibility, and to show both the complementarity (or mismatch) between the existing results and the knowledge gaps, we will place each studied configuration in the framework developed in section 1.

The official definition of food security, adopted at the FAO World Food Summit in 1996, states that "*Food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life*". This consensus definition sees food security as being based on 4 pillars (availability, access, utilization, and stability). The studies we examine are based on these pillars (to a limited extent for adequacy), most often by considering pillars simultaneously (typically when referring to stability).

1. Systemic risks to food security

Impact of correlated yield losses on food availability

The case of correlated yield losses is the most typical way of capturing systemic risks to food security in its availability dimension (Ben Ari et al., 2018; FAO, 2018; Parker et al., 2020; Ray et al., 2015). The issue of yield losses caused by environmental variability is a longstanding problem that is targeted by many risk mitigation strategies. These strategies rely on risk-pooling principles (Gaupp et al., 2017; Paut et al., 2019; Renard and Tilman, 2019) in which fluctuations can be reduced by diversifying the combination of crop products from different areas with different price fluctuation patterns (Feng and Hayes, 2016). But these strategies are challenged by the occurrence of large-scale crop failures, or correlated crop failures over long-distances (Gaupp et al., 2017). Systemic risk is understood here as resulting from exogenous shocks to physical systems. Exchange systems that are connected to production systems are supposed to reduce this systemic risk. Free trade agreements are based on the assumption that a yield loss in one region will be offset by an increase elsewhere, and that trade will balance supply and demand overall (Hosoe, 2016; Tanaka and Hosoe, 2011). Yet the case of correlated yield-losses among breadbaskets raises the issue of the inability of trade to compensate risks. Correlated crop failures across production basins and food items most often relate to climatic teleconnections occurring within large-scale climate oscillations such as ENSO, AMO or NAO (Anderson et al., 2019). If crop production is spatially concentrated, there can be no offsetting between production anomalies across continents in the case of abnormal events (e.g. maize production during the 1983 El Nino event).

Climate-change-induced extremes such as droughts may also cause synchronized failure over large distances (Beillouin et al., 2019; FAO, 2018; Parker et al., 2020; Tigchelaar et al., 2018). More generally, simultaneous losses across production basins are expected to become more likely in a +4°C world (Gaupp et al., 2020) notably due to the induced increased frequency of climate extremes (Kunimitsu et al., 2020; Mehrabi, 2020; Tigchelaar et al., 2018). Recent analyses in the context of extreme weather events have shown that losses, which are correlated within production basins, are correlated to an even greater extent in the case of extreme losses creating an additional barrier to adaptation (Gaupp et al., 2017).

The same problem of correlated yield losses exists for biotic risks that may for example affect entire regions of production on a subcontinental scale (Oerke, 2006; Saponari et al., 2018). Where production is highly specialized in space, these risks might threaten an entire production basin, for both animal and plant production (Moral et al., 2019). In so-called industrial systems (intensive monoculture, concentrated animal feeding operations), an absence of natural barriers may favor the spread of parasites, diseases and other pests (Kapan et al., 2006). Modern livestock farming practices encourage the emergence and spread of zoonoses (e.g. influenza A or SARS-1/2) through increasing population size and density (Jones et al., 2013).

Trade, stability and access

For a long time, it was considered that long-distance trade helped to stabilize markets and cope with climate risks or offset local resource limitations but over recent years, various authors have revisited this hypothesis and have explored how the benefits of the larger openness of nations might be offset by greater instability or environmental costs (D'Odorico et al., 2012; Dupas et al., 2019; Ercsey-Ravasz et al., 2012; Puma et al., 2015; Sartori and Schiavo, 2015; Seaquist et al., 2014; Suweis et al., 2011; Tamea et al., 2016; Tu et al., 2019a). Using the tools of complex network analysis (see section 1), they have studied the topology of the global food trade network to assess its vulnerability and resilience.

In particular, they have looked at how the international trade network has evolved over time, from the 1980s to the present day. The analysis of node degrees shows that the network exhibits high structural plasticity and evolves towards a better balance and less centralization (Carr et al., 2012; D'Odorico et al., 2012; Sartori and Schiavo, 2015). This means that over time major agricultural exporters have become less central, new exporting countries have emerged (e.g. Brazil), and weakly connected countries have been able to diversify their supply sources (Dupas et al., 2019). On the other hand, node strength (i.e. the importance of the flows for each link) shows different or even opposite results: the network may have become increasingly concentrated around a small number of hubs (Carr et al., 2012; Puma et al., 2015). In other words, the observed network diversification is mostly true for small trades, while larger trades become ever more centralized or more vulnerable, according to complex network theory. D'Odorico et al. (2012) studied the transformation of communities within the global agricultural trade network and showed that communities (i.e. a subset of densely connected nodes) tend to become stronger as the network grows. This strengthening of communities only corresponds in part to processes of regional integration. In principle, this increase in overall network modularity should improve network resilience, but a network's positive effects of modularity are dependent on other properties of the network, such as its connectivity and structure (homogeneity or heterogeneity of links, between imports and exports).

Another way to characterize the vulnerability of the trade network is to run a simulation of the effects of production shocks on the trade network, in order to assess its propensity to transmit the initial shock (through a reduction in exports) and potential disruptions at national or global scales. For example, Puma et al. (2015) simulate a continental-scale climate shock affecting major wheat or rice exporters. They show that the increase in connectivity has made the network more vulnerable to self-propagating disruptions with stronger effects across the least developed countries and those most dependent on imports (e.g. Haiti, Senegal). In their shock propagation model, Gephart et al. (2016) add the willingness of individual countries to pay (i.e. the fact that wealthier countries would arguably accept to pay more in order to maintain their supply) and show that the effect of a shock on poorer countries is even stronger. Food reserves can effectively mitigate the effects of such shocks on import-dependent or poorer countries (Marchand et al., 2016). Although the overall level of these reserves has declined since the 1990s, they are now more evenly distributed, providing greater capacity for individual countries to absorb shocks.

Access

Access to food depends on the relation between prices and household incomes. While global food price spikes occurred in 2008 and 2011, the propensity of international prices to be passed on to the consumer and turn into a global systemic food crisis still needs to be assessed (Hertel et al., 2001; Rosegrant et al., 2012). During the food price spike of 2007-2008, many observers warned against a looming food crisis (FAO, 2009). But a few years later, new data showed that the food price spike did not trigger a global increase in food insecurity (FAO, 2013; Verpoorten et al., 2013). Two factors might explain this result. Firstly, rising food prices do not affect net producers and net consumers in the same way. Given that in countries where the prevalence of food insecurity is high many of the most vulnerable are rural poor (and farmers), some food insecure countries might actually have benefited from the rise in agricultural prices (Headey, 2011). Secondly, international markets and domestic food markets are not yet fully integrated, especially in food insecure regions. In Africa, staple foods are not internationally tradable and cannot easily be replaced by imported products. In Sahel, for example, the dynamics of local coarse grain markets (millet and sorghum) are completely disconnected from international food prices (Daviron and Douillet, 2013; Minot, 2010). So due to inter- and intra-country heterogeneities, it is not clear that a price shock on international markets will necessarily result in a global food crisis.

Income is a major factor in access to food. The current Covid-19 pandemic and the lockdown measures introduced to control it also act as a natural experiment for a black-swan type of event. The dramatic economic downturn caused by the pandemic and by social restrictions in many countries of the world has resulted in an aggregate shock to the income and livelihoods of millions of households and individuals, directly threatening their food status. People with a low level of education and who rely on labor income are likely to be the most affected (Arndt et al., 2020). Socialized income, social protection and subsidized access to food could therefore play a major role in buffering the impact of the economic crisis on food security.

Arguably, the co-occurrence of a price spike and a real income shock would have a systemic impact on food security.

2. Food Security strategies as a source of systemic risk

Food security strategies can themselves be a source of systemic risk. Elements that in principle allow for a stable state thus create the conditions for systemic instability. Firstly, in a system understood as an exchange system, responses to a local food shock may in fact amplify its consequences and create a systemic risk at a larger scale ("social amplification of risk"). On a longer time scale, institutions regulating trade may unwittingly increase social inequalities and compromise access to food. Secondly, the systemic dimension of risk may result from the damage to ecosystems associated with human activities. Taking this physical dimension into account leads to a different conception of systemic risk and of ways of preventing it. In particular, while the domino effect paradigm carries a short-term vision of systemic risk (both in terms of its causes and of its consequences), taking into account feedback loops within ecosystems leads to greater attention being paid to the long-term build-up and consequences of systemic risk.

The social amplification of risk

While a significant amount of research is focused on the role that network topology plays in turning a local incident into a systemic crisis, some studies highlight the role of human expectations and behavior (Renn, 2008). In the case of food security, some research shows how a weather event with strictly local or regional consequences on agricultural production can become a global, systemic crisis due to inappropriate policy responses to price volatility. Indeed, such responses essentially take into account local or national considerations, without considering their international or even inter-sectoral consequences (Challinor et al., 2018). In the case of the 2008 food price crisis, export bans - designed to protect the populations of producing countries - may have played a major role in triggering the price spike (Headey, 2011).

The above-mentioned mechanisms relate mainly to short-term decisions. Some lines of social science research, rooted in the critical analysis of power in food systems and the role of institutions that underpin such power relationships (*food regimes*), propose a more structural approach to these mechanisms and to the institutional amplification of risk. These approaches study how the institutions of globalization relate to a geopolitics of food and how international agreements favor the establishment of multinationals in countries with a high prevalence of food insecurity (Clapp and Fuchs, 2009; Sommerville et al., 2014). Furthermore, while network and economic analyses have focused on the issue of import dependence, research on food regimes shifts the focus to two issues: the orientation of vulnerable countries' agriculture towards exports, and the transformation of these countries' diets through direct investments by multinationals seeking new consumers' markets.

Global farmland acquisitions (Peluso and Lund, 2011), driven by rising food prices and legitimized by global food security discourse (McMichael, 2012; Sommerville et al., 2014) would increase the vulnerability of food-insecure countries. These large-scale investments would contribute to evicting small farmers, and therefore reduce their livelihoods. Furthermore, such investments would be directed primarily towards export crops (Anseeuw et al., 2012). Globalization would also structurally alter consumption patterns, diets (increased consumption of processed carbo-hydrates), driving for instance the structural change of Body-Mass Index in countries of the global South, rural areas included (NCD Risk Factor Collaboration, 2019; Otero et al., 2018). As a consequence, systemic risk would endogenously result from institutional arrangements which entail, not only trade dependence, but also a risk shift from undernutrition to a more complex malnutrition issue (Benton and Bailey, 2019; Khoury et al., 2014).

Beyond market institutions and regulations, politics play a role in determining systemic risk to food security. It is worth recalling that in the 20th century (Ukraine, China, Biafra), and still today (Syria, Yemen), the worst famines were manufactured and caused intentionally, especially during armed conflicts (de Waal, 2018). While the use of hunger as a political tool is nothing new, nowadays it might interact with climate and economic risks. In which case systemic risk would result from the interplay between heterogeneous risks (Puma et al., 2018).

Systemic risks associated with the unsustainable food security strategies

We are now going to see how the very strategies meant to bring stability and enhance food security can endogenously exert powerful feedback effects on agroecosystems, create conditions for systemic instability, and drive irreversible change within those ecosystems. The effects of these feedbacks are generally delayed in time and/or space.

Since the twentieth century, the dominant strategy for achieving food security has been to intensify food production in order to increase food availability (Coomes et al., 2019). On the one hand, the increase in external inputs (fertilizers, pesticides, irrigation water) have contributed to fantastic increases in yields of most crop species, global crop production and reduced food insecurity for billions, thus helping to support global human demographic growth (Erisman et al., 2008; Tilman et al., 2011). On the other hand, however, the massive changes in land use for agricultural purposes and the intensive use of chemical inputs in agricultural systems is causing severe harm to both natural and agro ecosystems. Agriculture covers approximately 40% of Earth's terrestrial ice-free surface (Foley et al., 2005), accounts for a quarter of global anthropogenic greenhouse emissions (Smith et al., 2014), significantly adds nitrogen and phosphorus to land and water ecosystems (Steffen et al., 2015) and drives global contamination of natural and cultivated ecosystems by pesticides at the global scale and in the long-term (Maggi et al., 2019; Riedo et al., 2021; Stehle and Schulz, 2015). All those impacts are likely to have severe feedbacks on cultivated agroecosystems (e.g. on their level of soil organic matter, protection against soil erosion, soil microbial communities, pest regulation by their natural enemies), on their sustainability and on their productivity levels. Similarly, losses in cultivated and natural biodiversity are likely to drive important drops in crop yields due to losses in pollination and pest regulation related ecosystem services. We very much need to account for these endogenous feedbacks of agricultural production on the status and sustainability of agroecosystems in order to understand systemic risks to food security.

More recently, researchers have become more concerned with the feedbacks that trade exerts on agroecosystems. In this case, these feedbacks are spatially delayed and may remain invisible to consumers in importing countries. To assess this environmental footprint of trade, researchers evaluate the primary resources embedded in exported agricultural products. Seminal works on trade-related virtual water flows (Allan, 2005, 1998) have paved the way for the study of the *telecoupling* between distant social systems and ecosystems (Hull and Liu, 2018). Virtual water trade was initially seen as an efficient way to overcome limitations to food production resulting from local resource scarcity. But studies on telecoupling increasingly question trade, as a way to (unwittingly) offshore environmental risks (depletion of resources, soil pollution, see Galloway et al., 2007).

For example, while 52% of irrigation water is unsustainable, exports account for 15% of this unsustainable use, mainly for cotton, sugarcane, fruit and vegetable crops (Rosa et al., 2019). They also let us distinguish between "efficient" virtual water trade (from resource-affluent to resource-scarce regions, such as MENA) and situations where an already affluent country puts additional stress on water in an exporting country, due to its consumption structure (e.g. a European country importing exotic fruit from Latin America). Beyond virtual water, many countries consume natural resources for food that are far greater than those offered by their own ecosystems. For example, the Mediterranean basin consumes 2.5 times the resources its ecosystems provides (Galli et al., 2015). Some complex network studies also focus on the impact of trade on the stability and resilience of ecosystems (Suweis et al., 2015, 2013; Tu et al., 2019b) and suggest that the global relationship between population growth on the one hand and production and trade on the other induces an unsustainable imbalance in resources. Over the period 1986 - 2010, the number of such "unstable" countries increased. We might therefore be witnessing an increase in food insecurity and a decrease of the resilience of the coupled food-population dynamic.

3. Coping and management strategies

We will now examine the strategies employed to manage or govern systemic risks relating to food security. Overall, we can identify two types of strategy: instruments of governance and system transformation.

1. Instruments of governance

Crop insurance systems were developed as a response to correlated yield losses and their impact on food availability, but such schemes are risky (Miranda and Glauber, 1997) and therefore entail high premiums (Shen and Odening, 2012). While yield losses are correlated at a production-basin level, this is generally not the case at inter-basin or inter-regional levels (Gaupp et al., 2017). This has led some authors to recommend either the creation of joint-insurance pools at a national level, or even international insurance schemes (Gaupp et al., 2017; Porth et al., 2016). Climate change disrupts this insurance rationale, due to the prospect of extreme weather events occurring during the same season in different parts of the world. Some re-insurance companies (Lloyd's, 2015) are concerned that as far as agricultural crops are concerned, we might be shifting towards an uninsurable world.

Above and beyond the systemic risk to food availability, the main instrument for managing systemic risk to food security (in terms of access and stability) is the regulation of agricultural markets. In the face of price risk, several options have been tested in the past: the establishment of reserves, in order to smooth prices, the export of surpluses on international markets, or the setting of quotas. Conversely, another option is to open up and liberalize markets in order to balance production differences between regions. This logic of liberalizing agricultural markets, under the aegis of the WTO, has been in place since 1995. The 2008 price crisis and the return of price volatility brought the issue of market regulation methods back onto the agenda. In particular, this raised the issue (not provided for in the WTO agricultural agreement) of export bans (Headey, 2010). Moreover, it led to the question of the possible need for a stabilizer (or "lender of last resort") on international markets, be it a State or an international organization (Courleux and Depeyrot, 2017). The 2008 food price spike also reignited the debate on food reserves (European Commission, 2018), especially for developing countries where trade dependency is high.

Recognizing that the systemic nature of risks relating to food security requires new governance, one that goes beyond traditional risk management, a certain number of authors are proposing new risk analysis and risk assessment tools for decision-making.

In this regard, Chodur et al (2018) apply the Fault Tree Analysis (FTA) multi-level modelling tool to food systems. Based on the analysis of a system's failures, it allows one to describe and simulate interactions between the elements of the food system on the basis of one or more disruptive events affecting the axes of food security (non-availability, non-accessibility or non-acceptability). Such a tool makes it possible to accurately identify the system's points of vulnerability in a given situation and to prevent cascading failures that might disrupt the system as a whole. Sharif and Irani (2017) suggest that the characteristics of a VUCA world (volatility, uncertainty, complexity, ambiguity) have become structuring properties of food systems that it is futile to try to eliminate (through interventions aiming at a greater resilience, for example). From this standpoint, it is also necessary to try to characterize these states of instability in order to grasp certain particularities. Sharif and Irani suggest a new approach to decision-making based on the systematic comparison of the rational decision-making process (structured method) and VUCA perspectives (unstructured method), so as to build contrasting food security scenarios.

2. System transformation

Systemic risk management or governance aside, three main strategies for system transformation can be identified to reduce systemic risk in relation to food security: (i) increasing system resilience, (ii) system diversification and (iii) reducing connectivity. While the first two strategies essentially apply to agricultural systems, the third applies more to trade in goods and commodities. However, these strategies do not have the same transformative scope. Debates on agricultural models are nothing new, but whereas they used to focus on human health and environmental issues, they now also focus on the capacity of each model to offset the detrimental effects of climate change, and more generally on their intrinsic stability.

Technology is often used to increase robustness to adverse events. Faced with the dual imperatives of food security and ecological sustainability, some authors recommend developing more resource-efficient systems, in particular through technological innovation (Beddington, 2009). The transformative scope of these innovations remains limited, in as much as they do not lead to in-depth changes in agricultural systems (let alone diets) and may even encourage overexposure to risk (rebound effect). Other authors believe that promoting diversity, whether in time or space, can make it possible to reduce systemic risk and protect against food insecurity (Paut et al., 2019; Renard and Tilman, 2019).

A more transformative ambition to reduce systemic risk lies in agroecology, the advocates of which point out the harmful effects of an oversimplified food supply on human health (non-communicable diseases) and underline the mutual support between agroecology and the emergence of healthier diets (iPES-Food, 2016). This diversity in the types of food produced is supposed to improve the quality of diets, especially for small producers (Tesfaye and Tirivayi, 2020). The IPBES (2019) suggests that more diversified production systems (e.g. agroforestry, intercropping, cultivar mixtures or rotations) might help mitigate the negative effects of interannual climate variability (Pellegrini and Tasciotti, 2014) or even have intrinsic stability properties (Schrama et al., 2018). So far, this debate between extensive and intensive agriculture has mainly focused on how agricultural production impacts the environment (Kremen and Miles, 2012), and more recently on diet quality. But this debate can also be reinterpreted in terms of systemic risks to food security. The diversification strategy is turning on its head the dominant 20th century strategy, whereby agricultural modernization policies have consisted in reducing risk by increasing agricultural productivity through the simplification of agricultural systems. Many studies have shown that diversified systems can help improve a number of ecosystem services (Iverson et al., 2014), such as the management of weeds and pests (Duarte et al., 2018).

A third strategy consists in reducing system connectivity in order to lessen the contagion effects of risks, in commercial trade. Initially driven by social movements (food justice, agro-ecology), it is now being advocated by local authorities who are trying to set up local supply systems (Sonnino, 2016) as part of a food sovereignty policy. These supply strategies are designed to limit the risks of disruptions in supply to metropoles and to increase the health quality of products. Advocates of agroecology and of a major transformation of diets to improve food and nutritional security also highlight the fact that the main lever of transformation is the organization of trade and the implementation of local food systems (iPES-Food, 2016).

Figure 2 maps the various strategies for mitigating systemic risks for food security on the systemic risk diagram.

Figure 2

Strategies to mitigate systemic risks to food security (green) can be classified along the two axes of the diagram presented in Figure 1

4. Discussion and conclusion

In this review paper, we have argued that there are different ways to characterize systems (interaction, common physical properties) and that, when addressing food security, researchers should pay attention to the interactions between the exchange dimension and the material dimension of food systems. The articulation of network analysis and virtual resource accounting is one way to integrate these interactions. Researchers should also bear in mind that the interdependence resulting from common material properties differs from that resulting from social interaction: while everyone is, by definition, connected to and depends upon the Earth system, not everyone is connected to international trade. Extreme weather events can propagate across a network, but they may also hit regions which are poorly connected to international or regional markets, and this might actually be a bigger threat to food security.

Moreover, there are various ways to model the mechanisms that cause systemic events. The domino effect model relates to the propagation of a local shock to a set of interacting agents and captures the short-term processes and consequences associated with an exogenous perturbation. We have insisted that scholars should also take into account endogenous processes of feedback between food system elements, along with the long-term accumulation of loads within a system, which might eventually lead to a disruption.

In terms of topics, and unsurprisingly when it comes to food security (Davis et al., 2021), systemic risks have primarily been addressed with regards to food production. Over the past decade, with rising concerns over international trade and import dependency, research has made tremendous progress in tackling trade-related systemic risks and their interaction with sustainability issues. The issue of food adequacy, nutrition, diet change and cultural patterns have only been touched upon (Reardon et al., 2021) and could usefully be included in approaches to systemic risk. The reliability of the data used to model systemic risk is also an issue. Most of the studies presented in this paper use FAOSTATS datasets, which rely on national customs for trade data. In sub-Saharan Africa for example, a major part of regional trade is not registered by customs and is therefore largely underestimated (Bouët et al., 2021). Beyond data reliability, using countries as individuals generates a statistical fiction and may obscure two important phenomena: intra-country heterogeneity and the role of firms and producers' organizations in trade.

The concept of systemic risk has a transformative scope. In finance, it is used by central banks to better regulate the market in order to prevent financial crises. As we have seen in Section 1, the way in which one defines a concept, models processes or chooses data is not neutral and affects the way in which one perceives reality and acts upon it. We suggest that different approaches to systemic risk result in different political agendas. While they all put on the table the issue of free trade and the need for additional regulations, we can nevertheless distinguish between at least two different systemic risk agendas. One that naturalizes connectedness, globalization and the occurrence of disasters and which promotes interventions meant to prevent disruptions (or mitigate their consequences); and one that adopts a long-term view, pays attention to the inequalities and imbalances that result from food system activities, and scrutinizes how systemic risk builds up through chronic exposure.

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