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REVIEW

Towards metrics of sustainable food systems: a review of the resilience and vulnerability literature

Paolo Prosperi[1] · Thomas Allen[1] · Bruce Cogill[2] · Martine Padilla[3] · Iuri Peri[4]

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Abstract Food and nutrition security is a persisting global issue and, in addition, food systems are now facing a new set of intersecting economic, social and environmental challenges. Recurrent socio-economic and biophysical changes put the sustainability of food systems at risk. There is an urgent need to develop knowledge-based tools to assess and monitor food sustainability and to identify pathways for food security and resource conservation. The systemic nature of these interactions calls for multidimensional approaches and integrated assessments for decision-making to guide change. This paper reviews social–ecological system frameworks with the view to conceptualize the sustainability issues that affect the food systems. It is argued that the understanding of the food systems as social–ecological systems, and inputs from the theories of vulnerability and resilience in particular, can provide the concepts necessary to understand and model the complex system dynamics involved in the multiple interactions between human and natural components.

Keywords Food and nutrition security · Sustainable development · Resilience · Social–ecological systems · Systems of information

P. Prosperi and T. Allen are first co-authors.

✉ Paolo Prosperi
p.prosperi@cgiar.org

Thomas Allen
t.allen@cgiar.org

1 Bioversity International, Parc Scientifique Agropolis II, 34397 Montpellier, France

2 Bioversity International, Via dei Tre Denari, 472/a, Maccarese (Fiumicino), 00054 Rome, Italy

3 Mediterranean Agronomic Institute of Montpellier (CIHEAM/IAMM - UMR Moïsa, Markets, Organizations, Institutions and Operators' Strategies), 3191, route de Mende, 34093 Montpellier, France

4 Department of Agriculture, Food and Environment, University of Catania, Via Santa Sofia, 100, 95123 Catania, Italy

1 Introduction

Food insecurity[1] is a persistent global issue, and the food system is now facing a new set of intersecting social, environmental and economic challenges. Food security depends on ecosystems and associated services, and during the last 50 years, the physical and functional availability of ecosystem services has fallen faster than ever before (IAASTD 2009). Global environmental change, apparent in climate change, ocean acidification and biodiversity loss, has a growing impact on stocks and flows of ecosystem services at a global level (Ingram et al. 2010). Besides environmental change, numerous socio-economic factors bear critical responsibilities in food systems and drive food security outcomes.

Food systems rely on physical resources such as land, water, biodiversity and fossil fuels, which are becoming ever more fragile and scarce. Meeting the food demand remains challenging due to disturbances brought by global

[1] The current definition of food security, used by FAO, IFAD and WFP, considers food security as "A situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life. Based on this definition, four food security dimensions can be identified: food availability, economic and physical access to food, food utilization and stability over time" (FAO, IFAD and WFP 2015).

changes. The food system is partially responsible for these changes through its own activities, which in turn hamper the availability of resources for sustaining the perpetuation of the food system functions (Misselhorn et al. 2012).

Increasing economic and social inequalities, market and political instability and shifting consumption patterns hinder the global food system, with consequences such as the double burden of malnutrition[2] (Garrett and Ruel 2003). The world population is growing rapidly, and diets are shifting towards an increasing demand for meat products. Concurrently, modern agriculture still depends on oil coming from fossil reserves and biofuel production (Ericksen 2008a; Cabell and Oelofse 2012). The latest FAO estimates indicate that approximately 805 million people are chronically undernourished worldwide (FAO, IFAD, WFP 2014). Considering that the global population is projected to reach 7.3 billion in 2015 (UN 2014), it is possible to estimate that 11 % of people suffer from chronic undernourishment (FAO, IFAD, WFP 2014). Concurrently, nearly 2.1 billion people are affected by malnourishment related to unhealthy food consumption and dietary patterns, which is reflected in the spread of food-related diseases like obesity and cardiovascular diseases (Ng et al. 2014). At the same time, food production and consumption impact the environment and are significant sources of greenhouse gas emissions. Evidence related to this global change is observed through worldwide-reduced yields (Lobell et al. 2011). Agriculture alone is responsible for 70 % of water withdrawal (FAOSTAT 2015) and represents a main driver of deforestation and biodiversity loss.

These evidences show the crucial contradictions and challenges that the food system is facing. Efforts, therefore, need to be focused on the creation of food systems that are more efficient in the use of resources and reduce food waste at every stage from primary production to transformation and consumption (UNEP 2012). There is an urgent need for developing knowledge-based tools to assess and monitor sustainability of food systems and to identify pathways for food security and resource conservation.

In order to link these different challenges, and building on a broad definition of food system, food security can be deemed as the outcome of several different activities. This perspective allows Eriksen and Kelly (2007) to suggest a socio-ecological system (SES) approach for the analysis of the food system, incorporating environmental, social, political and economic determinants summarized in socio-economic and global environmental change drivers (Gerber 2014). Thus, food systems are considered social–ecological systems (SESs) that comprise biophysical and social factors linked through feedback mechanisms (Berkes et al. 2003; Ericksen 2008a) (Food system framework: Fig. 1). Food and nutrition security is underpinned by food systems (Ingram et al. 2013) and relies on several properties of food systems, categorized as a range of activities: producing, processing and packaging, distributing, retailing and consuming, that emanate in three main sets of outcomes, namely food and nutrition security (availability, access, utilization), social welfare and environmental capital. Furthermore, various elements of food systems are altered by, and actively impact, the socio-economic and environmental conditions of the system across local, regional and global levels. These interactions are featured by, and bring with themselves, high uncertainties (Ericksen 2008a; Ingram et al. 2010; Ingram 2011). Food and nutrition security then is considered the principal outcome of any food system (Ericksen et al. 2010) and is a multidimensional concept that can be analysed at individual, household, community, national, regional and global level (Ingram 2011). Food security depends on multiple biophysical drivers—strongly linked to global environmental changes such as land and water resources degradation, biodiversity loss and transformation, see level rising—and economic and social stresses—such as demographic dynamics, scientific and technological innovation, global economy trends, food sector structure changes, social inequalities—that interact with each other and then impact, individually or concurrently, on different aspects of the food system (Ingram et al. 2013; Ericksen 2014). Such drivers might impact food security directly or indirectly, positively or negatively; when a food system fails to deliver food security, the system can be considered as vulnerable (Ericksen 2008a, b, c).

The systemic nature of these interdependencies and interactions calls for systems approaches and integrated assessment tools. Identifying and modelling the intrinsic properties of the food system, that will ensure its essential outcomes are maintained or improved over time and across generations, will help decision-makers and policy-makers to trace progress towards sustainability and implement policies that foster positive transformations. The analysis of food system sustainability aims at identifying the key properties of the system for supporting life, including food and nutrition security that is the first normative reason for being of food systems (Haddad 2013), by examining the multicausality of dynamic processes within a complex food system. This could help understand changes over time on food security and social and environmental outcomes.

These outcomes are also determined by decisions and actions taken along the activities of the food system, but also by global socio-economic, political and environmental drivers through their impacts on the food system (Ingram

[2] "The Double Burden of Malnutrition is the coexistence of undernutrition and overnutrition in the same population across the life course" (Shrimpton and Rokx 2012; p. ix).

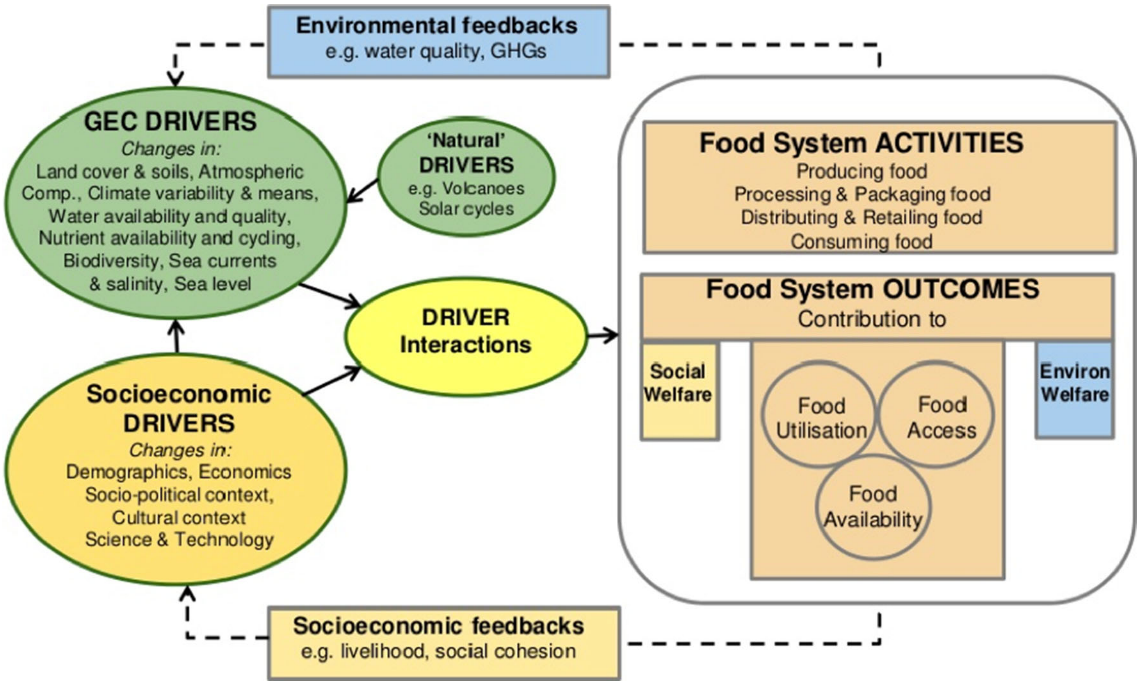

Fig. 1 Ericksen's (2008a) food system framework: the Global Environmental Change and Food Systems (GECAFS) research project (original diagram by Ericksen's (2008a))

et al. 2010). Thus, agricultural and resource management problems can be categorized as system problems. Aspects of food systems' behaviours are complex, difficult to anticipate and have multiple causes. In natural and social systems, and their interplays, problems are often nonlinear, dynamic and cross-level in time and space. It is thus necessary to have a systems perspective where feedbacks occur across temporal and spatial scales. In order to explore and identify the appropriate strategies of response to the interactions in a changing, coupled human–environment system in relation to food and agriculture, interdisciplinary and integrated analysis methods are needed.

There is a call for more inclusive, social–ecological, system-oriented approaches that look at the resources (financial, physical, natural and social) to capture the dynamic processes between and within the food system activities, nutrition and health, and environmental outcomes (Ericksen 2006, 2008a; Thompson and Scoones 2009).

Understanding what needs to constitute the assessment of the sustainability of food systems and diets is the key for providing decision-making and policy-making with knowledge of action, and having a systemic rationale and a framework to build a metric system is indispensible (Fanzo 2014). There is yet no single recognized metric to assess the sustainability of a food system (Vinceti et al. 2013). Indicator system or metrics are, however, important tools to synthetize and present complex data and trends to decision-makers and policy-makers (Bell and Morse 2010). A consistent range of evidence-based indicators and standards needs to be defined in order to conduct analyses of the quantitative linkages and trade-offs between food security, nutrition, health, agricultural productivity, resource use and environmental impacts (Beddington et al. 2012; Fanzo et al. 2012; Johnston et al. 2014). This paper provides a literature review of some conceptual approaches that better link joint issues related to food security and sustainable development. We argue that the resilience and vulnerability literature, which emanates from the SES frameworks, can provide some of the concepts to better frame the principles of sustainable food systems and identify those elements that should be monitored and assessed.

Section 2 describes food systems as complex social–ecological systems, involving multiple interactions between human and natural components. The systemic nature of these interactions calls for multidimensional approaches, integrated assessments and simulation tools to guide change. Major concepts of SES frameworks, such as vulnerability and resilience, are presented. In Sect. 3, a review highlights the contribution of vulnerability and resilience to sustainability analysis of food systems, discussing pros and cons. A focus on the gaps in common approaches for the assessment of the sustainability of a food system concludes this article, sketching out some ideas on how to develop such evidence-based systems of information.

2 Social–ecological systems frameworks

Foran et al. (2014) comprehensively synthetize what is generally intended by the term "social–ecological system" according to a diagnosis of complex and systemic food security problems: "SES visualizes the human–environment interface as a coupled 'system' in which socio-economic as well as biophysical driving forces interact to influence food system (and sub-system) activities and outcomes, both of which subsequently influence the driving forces" (p. 90). SESs are dynamic systems that are continuously changing in response to internal or external pressures (Berkes and Folke 1998; Schlüter et al. 2014), and the literature concerned was initially primarily oriented towards environmental change and the medium- and long-term impacts of human activities on future human prosperity (Foran et al. 2014). SESs involve societal (human) and ecological (biophysical) subsystems in mutual interaction (Berkes and Folke 1998; Folke et al. 2002; Gunderson and Holling 2002; Walker et al. 2006). Most complex phenomena involving concurrently social and ecological systems are indivisible, and any differentiation is thus considered counterfeit and subjective (Berkes and Folke 1998).

2.1 Food systems as social–ecological systems

Food systems can be considered as complex social–ecological systems (Ericksen 2008a) spanning the biological and socio-economic processes encompassed in the production, distribution, marketing, preparation and consumption of food (Misselhorn et al. 2012).

Building on Roe's method (1998) of triangulation of conceptual frameworks, Foran et al. (2014) chose a set of four dissimilar groups of conceptual frameworks oriented towards a rigorous analysis of the complexity in food systems in order to improve interdisciplinary interactions and the understanding and interventions in food security dynamics. This comparative analysis involved the conceptual framework groups of "agroecology", "agricultural innovation systems", "social–ecological systems" and "political ecology". The authors observed that SES frameworks emerge within the other sets with respect to problem framing. In fact, SES frameworks highlight cross-level and cross-domain interactions in a system, while the other sets of frameworks opt rather for focusing on a particular domain or level. SES frameworks arise as system-oriented frameworks that give further priority to complexity, analysis of systemic interactions and problem identification (Foran et al. 2014). From this analysis, it is possible to observe that SES frameworks appear to further emphasize the understanding of the relationships and the behavioural conditions of food systems faced with global change.

Alternatively, Binder et al. (2013) compared ten established conceptual frameworks that are meant to analyse social–ecological systems, namely "driver, pressure, state, impact, response", "earth systems analysis", "ecosystem services", "human environment systems framework", "material and energy flow analysis", "management and transition framework", "social–ecological systems framework", "sustainable livelihood approach", "the natural step" and "vulnerability framework". These conceptual frameworks were identified to allow an organized and interdisciplinary reflection on the complex issues in social–ecological systems. With regard to contextual and structural criteria, however, it is possible to find critical divergences within these frameworks, especially for the conceptualization of the ecological and social systems and their interconnections (Binder et al. 2013). The conceptual frameworks were classified into four groups by their contextual and structural characteristics: ecocentric, integrative, policy and vulnerability frameworks. The SES framework is here considered an integrative framework, featuring various types of feedback loops operating within the social system and between the social and ecological systems in different timescales. As argued by Binder et al. (2013), the SES framework approach emerges among the other frameworks as potentially the best candidate for gathering and diffusing pertinent data on the social and ecological systems to be applied in any framework, and as a common research approach for interdisciplinary analyses of social–ecological systems with the precise goal of combining disciplinary and methodological bounds (Epstein et al. 2013).

Initially, the SES framework originates from the literature on ecosystem management and ecology and has significantly contributed to adaptation to global environmental change reasoning of natural resource management (Foran et al. 2014). The SES framework embodies the theories of resilience and vulnerability (Foran et al. 2014) and in the last decade has been successfully applied to food systems (Eriksen and Kelly 2007; Ingram et al. 2010).

Accordingly, it is assumed that a SES frameworks perspective for enlightening food security would lead to enhanced resilience in various specific food systems domains through increased knowledge of systemic interactions, institutional transformation, diversity and connectivity between subsystems (Ingram et al. 2010; Foran et al. 2014). Several investigations from various discipline perspectives were led on food and nutrition security through the lens of vulnerability. Socio-economic studies find the causes of vulnerability, at both the level of the individual and at various group levels, mainly in socio-economic and political factors (Gorton et al. 2010). Other studies focus on impacts of and responses to environmental change, floods and droughts in vulnerable regions, and the connection to governance, inequality problems and physical and social geography factors (Fraser 2006, 2007; Ericksen et al. 2009; Eakin 2010; Misselhorn et al. 2010a, b; Ingram 2011).

2.2 Defining vulnerability and resilience of a food system

Global food security is facing several challenges. The global food system is rapidly changing and in the meantime is being confronted with surrounding global socio-political and ecological changes (Cabell and Oelofse 2012). Human societies, however, have the ability to anticipate and modify these changing trends (Holling 2003).

Over the last quarter of a century, a host of efforts, mainly from agricultural sustainability studies, have been oriented towards the ability of food systems to absorb stress while keeping their original functions (Conway and Barbier 1990; Conway 2007; Thompson et al. 2007). Consistently, Misselhorn et al. (2012) state that a resilient food system enhances food security and is able to minimize, withstand and anticipate environmental and economic disturbances at different temporal and spatial levels. In particular, the goal of achieving food security needs to build on a proper balance according to all the possible scales of action and the functions characterizing a food system, and also taking appropriately into account all its specific and potentially antithetic attributes such as connectivity and self-reliance, or change and stability (Hodbod and Eakin 2015). In addition, Berkes et al. (2003) and Gunderson and Holling (2002) find that shocks and perturbations potentially represent opportunities for innovation and transformation; in a resilient system, opportunity for learning and innovation is usually generated by a higher capacity of the system to cope with perturbation (Hodbod and Eakin 2015). On the other hand, a food system is considered vulnerable when it fails in delivering one or more of its intended outcomes and significant social–ecological consequences can be caused by even the smallest of stresses impacting the system (Adger 2006; Ericksen 2008a, c; Eakin 2010; Hodbod and Eakin 2015).

Vulnerability, as the propensity or predisposition to be adversely affected (IPCC 2014), of a food system is a function of exposure, sensitivity and resilience (Turner et al. 2003; Ericksen et al. 2010), and food systems can be vulnerable, and resilient, to a set of stressors (Adger 2006) such as environmental pressures, socio-economic instabilities and institutional and policy factors. The well-known Turner et al.'s (2003) framework for vulnerability assessment (Fig. 2) helps draw linkages between socio-economic (human influences) and biophysical (environmental influences) causal factors within a given coupled human–environment system and identify perturbations and stressors/stresses that interact with each other and emerge from these conditions and processes. Exposure (i.e. individuals, households, states, ecosystem that are threatened), sensitivity (i.e. human and environmental conditions) and resilience (enhanced through adjustments and adaptation) provide the concepts to identify the system's properties that shape a causal pathway towards food system's outcomes. This kind of framework is often considered difficult and complex to apply (Turner et al. 2003; Gbetibouo et al. 2010); however, a system analysis still needs to take into account the nonlinear mechanisms that regulate complex systems; it allows elaborate multidisciplinary perspectives, and it fills in science and policy gaps. The analysis of the vulnerability of a geographical area needs to take into account the complex spatial and temporal interconnectedness and feedbacks that govern the achievement of the outcomes (supply, access, utilization) of all the activities and steps contributing to food and nutrition security (Eakin 2010).

The concept of vulnerability has been adopted and largely explored in several disciplines and from various scientific communities referring to ecology, public health, human development, natural disaster, climate change and global environmental change, livelihood security, sustainability science and risk and resilience (Adger 2006; Füssel 2007; Cordell and Neset 2014). Vulnerability assessment belongs, in general, to a context and an area of study defined by natural or artificial boundaries (Downing and Patwardhan 2005; Schröter et al. 2005). Apart from broad assessments of vulnerability to global environmental change (Rockström et al. 2009), climate change vulnerability is most often analysed at a regional and local level since vulnerability is strongly context specific; an assessment method could be appropriate in one region but inadequate in another area (Fraser 2007; Cordell and Neset 2014).

Resilience is closely related to vulnerability in social–ecological systems and implies concepts of adaptation, transformation, innovation, self-organization and the capacity to perpetuate the activities over time despite the occurrence of stressors (Adger 2006; Folke 2006; Cutter et al. 2008). Resilience is a characteristic of complex and interrelated social–ecological systems that provides the system with the ability to absorb perturbations and also with the capacity to benefit from change through generating opportunities for development and innovation (Adger 2006; Resilience Alliance 2010; Rockström 2003).

When using vulnerability and resilience concepts, it is important not to simply consider them as antonyms. Vulnerability in social–ecological systems depends on the stress to which a system is exposed and on its sensitivity (the potential impact), and then on its adaptive capacity and resilience opportunities (the recovery potential) (De Lange et al. 2010); it relates to the structural changes occurring in

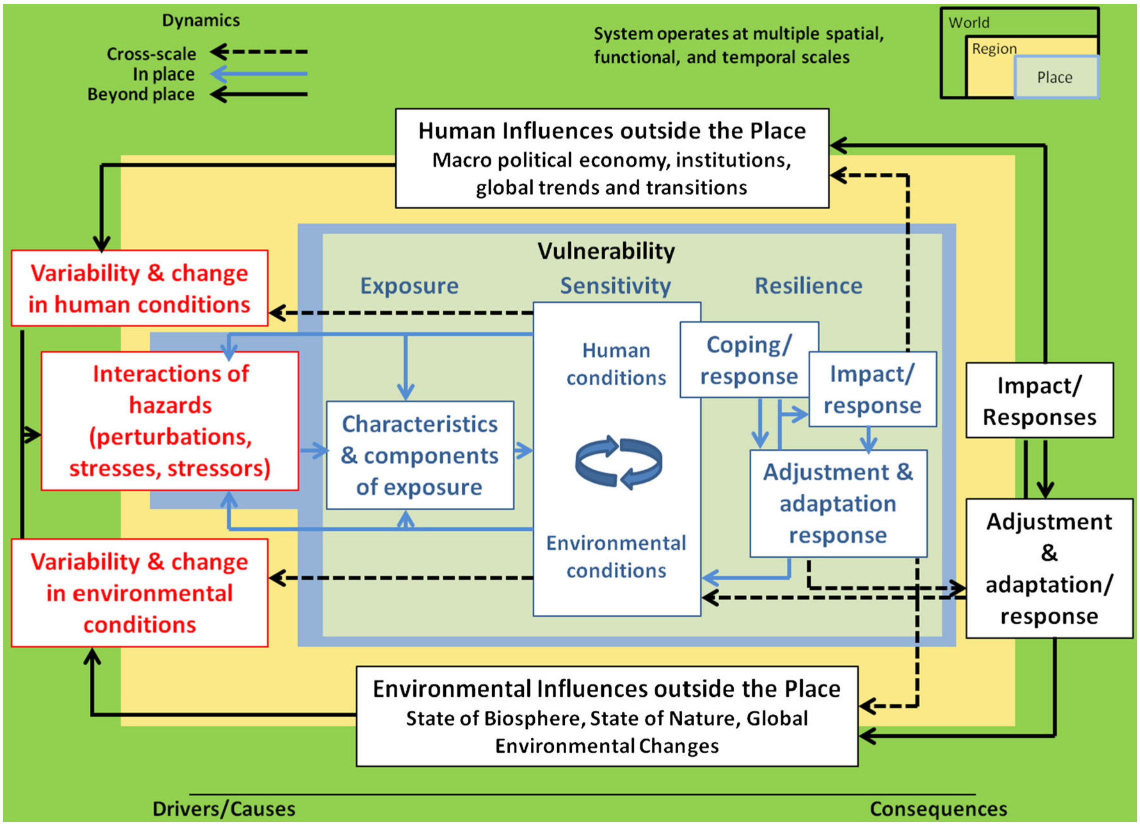

Fig. 2 Turner et al.'s (2003) vulnerability framework (figure retrieved from Ciurean et al. 2013)

a system and in its stability. Resilience, together with adaptive capacity, is thus a component of vulnerability. These three concepts describe the different expressions of the process of response to a change in the dynamic interactions between an open system and the surrounding environment (Gallopín 2006).

2.3 Vulnerability of the food system to global change

Contemporary food systems are characteristically cross-level and cross-scale (Liverman and Ingram 2010) and rely on a large set of biophysical and socio-economic factors. Food and nutrition insecurity is the final result of a number of interactions between global environmental changes and various socio-economic dynamics. The effects of these interactions are observed in given exposed areas or populations. The simultaneous occurrence of several nature- and human-related drivers of change, such as climate change, natural resource depletion, habitat loss and pollution, shifting dietary patterns, financial speculation on food commodities and oil extraction, threatens the ability of a global food system to maintain its vital functions and processes (Allen et al. 2014). As such, food and nutrition security is a global issue, pertinent in both developed and developing countries (Brunori and Guarino 2010). The drivers of change affecting the food system can be identified in five main categories, namely environmental, economic, social, technological and political (Brunori et al. 2008).

In recent vulnerability analyses, climate change is one of the most highly studied topics. Since the early 1990s, numbers of scientific studies concerning climate vulnerability have increased regularly over time (Tegart et al. 1990; Adger and Kelly 1999; Klein and Nicholls 1999; Kelly and Adger 2000). In recent years, investigations have advanced by incorporating social vulnerability into studies of climate change, environmental disturbances and adaptive capacity (Fraser 2003; O'Brien and Leichenko 2003; O'Brien et al. 2004; Ericksen and Woodley 2005; Schröter et al. 2005; Füssel and Klein 2006; Parry et al. 2007; Cordell and Neset 2014). As mentioned above, there exists an interplay between the impacts of climate change and other changing dynamic mechanisms belonging to different economic, political, temporal and biophysical domains (such as poverty, gender inequality, food price increases and natural resources depletion) on a local, regional and global scale (Fraser 2006; Ericksen et al. 2009). In such uncertain dynamic conditions, implementing linear policies becomes difficult (Funtowicz and Ravetz 1993; Kriegler et al. 2012; Vervoort et al. 2014).

Greenhouse gas (GHG) emissions and changes in land use, engendered by food system activities, strongly contribute to climate change. These activities, however, appear responsible also for other aspects of global environmental change, such as alteration of freshwater quality and supply, biodiversity, land cover and soils, nutrient cycling and air quality (Liverman and Kapadia 2010). Furthermore, GHG emissions directly affect temperature, freshwater availability and numerous parameters of climate change. Increasing water shortages and extreme weather events are associated with yield reduction and instability, and a decrease in areas suitable for traditional crops (Olesen and Bindi 2002; Olesen 2006). Climate change and natural resource depletion alter the world's food supply and indirectly impact prices and quantities, and hence trade (Godfray et al. 2010; Ingram et al. 2010), that in turn have serious impacts on food availability and affordability (Wood et al. 2010).

Both climate and non-climate drivers affect food systems. For example, non-climate drivers such as urbanization and pollution, and other socio-economic processes (including land management change) directly and indirectly influence social–ecological systems (Rosenzweig et al. 2007). Globalization, trade internationalization and a plethora of global forces, such as changes in demographic, economy, politics and environment, transform food production and consumption patterns, including marketing, and influence many food-related context-specific practices (Oosterveer and Sonnenfeld 2012). Resulting unbalanced food systems are likely to threaten the ability of the Earth to provide enough food in the future. For instance, food production in Europe is quickly outstripping regional and global environmental capacity, particularly with regard to nitrogen synthesis, phosphorus use, land use and degradation and the dependence on fossil fuel. The 2007–2008 food crisis demonstrated such a complex interconnectedness of the food system with environmental, financial and energy crises calling for interventions of mitigation (Brunori et al. 2008).

Complex system processes imply that manifold interactive pathways of change and environmental feedbacks and social responses to a change or driver can generate further changes that resonate throughout social–ecological systems. These phenomena and perturbations are not entirely controllable or predictable (Ericksen 2008c; Eakin 2010). Thus, building on a wide understanding of food systems, the interactions between and within biogeophysical and human environments regulate a set of activities directed at the achievement of food security outcomes (availability, access, utilization) that are consecutively altered by several factors (Ziervogel and Ericksen 2010; Bausch et al. 2014). Therefore, in complex and adaptive food systems it is not possible to forecast food security outcomes by means of conventional command-and-control approaches. There is then a call for a deeper and common analysis of causality dynamics characterized by the complex interplay of socio-economic, environmental, technological and global political factors around the food system (Ingram 2008). Vulnerability and resilience of agrofood systems originate from several sources that interact to engender unpredictable responses, and system thinking is the key to account for the interdependencies between drivers, feedback loops and nonlinear trends (Brunori et al. 2008).

The aim, thus, is to build resilient food systems to achieve food security and maintain desirable ecosystem states and services despite global environmental pressures (Folke et al. 2002; Gunderson and Holling 2002; Fraser 2003; Walker et al. 2006; Challinor et al. 2007). Responding to this necessity is the key to closing the gap in the understanding of the interactions among food security, vulnerability, resilience and ecosystem services (Ericksen 2008a, b, c).

3 Vulnerability and resilience to explore the sustainability of food systems

3.1 Research analyses of food systems and food security through SES frameworks

As stated above, resilience, vulnerability and adaptability have long been employed within the SES frameworks by different research areas and reflect the emergent properties of a system concerning its ability to respond to a changing environment and are strongly context dependent, especially in spatial and temporal scales and perspectives (Carpenter et al. 2001; Cabell and Oelofse 2012; Callo-Concha 2014). The SES frameworks and the theories of vulnerability and resilience have been suggested and applied, through different approaches, to the study of food systems, at regional and subregional levels, by several international research teams and institutions. Four approaches, of differing size and calibre, are reported here as examples of applications of SES frameworks and vulnerability and resilience theories to the analysis of food systems. While this paper focuses on the importance of determining metrics of sustainable food systems through the vulnerability and resilience theories, not all the following examples aimed merely at identifying indicators; however, they might represent some interesting opportunities for operationalization of the vulnerability and resilience theories towards the identification of metrics of sustainable food systems.

3.1.1 Global Environmental Change and Food Systems (GECAFS)

GECAFS was a 10-year-long (2001–2011) international and interdisciplinary research comprehensive program aimed at understanding the relationship between food security and global environmental change. A major objective of GECAFS was to identify strategies to cope with the impact of global environmental change on food systems and to determine the environmental and socio-economic consequences of adaptive feedbacks towards food security through improving understanding of the interactions between food systems and the Earth System's key socio-economic and biogeophysical components. The project delivered an innovative conceptual and analytical framework (Fig. 1) as well as analysis and methodological tools to investigate how global environmental change affects food security at a regional scale, strengthening multidisciplinary efforts and engaging development communities in policy discussions to improve food security (Gregory et al. 2005; Ingram et al. 2010). Recommendations for assessment are suggested in order to focus not only on the impacts of global environment change through indicators of food production, but to track these impacts on other related food system activities (Wood et al. 2010). It is highlighted the opportunity for future monitoring building on a high availability of existing data and information on indicators of vulnerability that can still be gathered, as well as the need for coordination of assessments of food system activities and outcomes in order to avoid overlapping and data redundancy. Also, it is stressed the importance of the choice of the information retrieved and how the information is communicated and perceived to and from the key stakeholders. The food system framework identified is then proposed for structuring and monitoring key variables of sustainable food systems, for further applications and predictions on future adaptations to global environmental change (Misselhorn et al. 2010a, 2010b).

3.1.2 2nd EU Standing Committee for Agricultural Research (SCAR) Foresight Exercise

In the 2nd Foresight Exercise (2008) of the SCAR of the European Union, it was considered insufficient to simply look at the multiple dimensions of food security (availability, access and utilization) and it was thus proposed that the analysis be enlarged to the several biophysical and socio-economic constraints that are determinants of a state of uncertainty of the food system. The foresight report attempts to answer, from a system perspective, the explicit question "how to reduce the vulnerability of social, economic and ecological systems", exploring the risks and opportunities emerging from systemic feedback loops, and linking the approach of vulnerability to the concepts of ecosystem services and sustainable development. The report identified, described in detail and justified several sets of drivers of change (economic, social, environmental, technological and policy) at a global and European level. Furthermore, it was stressed the need for validated and official indicators to feed policies, in particular with regard to the sources of vulnerability and resilience of the food system and to the impact assessment of policy measures to address them, to the measurement of public goods and the analysis of the drivers of change, to the assessment of the state and performance of European agricultural knowledge systems, and to the impact of food consumption style on the environment (Brunori et al. 2008).

3.1.3 TRANSMANGO

TRANSMANGO is an ongoing EU 4-year research project taking place within the "7th Framework Programme" that aims at obtaining a comprehensive image of the impacts of the global drivers of change[3] on European and global food demand, raw material production and food flows. The research focuses on the vulnerability and resilience of European food systems in the context of socio-economic, behavioural, technological, institutional and agroecological change and aims to improve the understanding of the new challenges and opportunities that the food sector will face in the future. The evaluation of the vulnerability and resilience of current and future European food systems—supported by a multidimensional analysis of social, environmental, agribusiness, nutritional and poverty indicators—is conceived at different levels to pinpoint directions for European policies. Through this systemic and modelling approach, with the involvement of a wide range of stakeholders, and by designing scenarios for the desired transition pathways in the food system, the project aims to understand the sustainability frontiers of different food production systems (TRANSMANGO 2014).

3.1.4 Metrics of Sustainable Diets and Food Systems

"Metrics of Sustainable Diets and Food Systems" is a multi-institutional project (Bioversity International and CIHEAM-IAMM 2014) that aims at exploring the different approaches to the assessment of sustainability of diets and food systems, establishing a multidisciplinary task force of experts and identifying a shortlist of indicators for sustainable diets and food systems. The initial focus was on

[3] Namely climate change, economic concentration and market structure, financial power, resource competition, marginalization, property rules, geo-political shifts, consumer preferences, consumption patterns and nutritional transition.

the Mediterranean region. The research approach builds on the assumptions that sustainability assessment aims at capturing the ability of a system to maintain and enhance its essential functions over time, and that sustainability addresses threats to preserving life support systems, including their capacity to withstand and adjust. Assessment of stocks of and changes to human and natural assets was considered crucial. Derived from sustainability sciences, the scientific approach was based on the theories of vulnerability and resilience within the social–ecological systems frameworks, in order to analyse the sustainability of critical food and nutrition security issues. A double set of drivers of change and context-specific food and nutrition security issues was identified at a subregional or national level. This theoretical modelling exercise allowed the identification of a first suite of indicators. Inputs from a multidisciplinary group of Delphi participants helped in particular identify specific metrics for evaluating the issues related to the nutritional quality of food vis-à-vis biophysical changes, such as water depletion and biodiversity loss. Also, the study of issues related to the affordability of food confronted with food price volatility has brought to the definition of the indicators needed. Still, further research is needed for analysing the potential impacts of the loss of biodiversity on issues related to the satisfaction of food preferences, and the potential interactions between the changes in consumption patterns and the dietary energy balance, in order to identify the most valuable and specific metrics. A reduced pool of metrics was then obtained through a structured expert-based elicitation process (Delphi survey), moving beyond subjective evaluation and reaching consensus (Allen and Prosperi 2014; Padilla et al. 2015).

The common thread that links these four programs, differing in size and aim, is the approach that is based on the dynamic perspective of the social–ecological systems and the related and complex interactions occurring around and inside the food systems. The concepts of vulnerability and resilience are adopted, even if through different applications and goals, with respect to the different understanding of the sustainability of the food systems. The GECAFS project focused mainly on human activities within the food system and operated on decision support systems to communicate GEC issues to policy-makers in a structured and systematic manner, and integrated social and natural science understandings of how food systems are vulnerable to global environmental change (through the concepts of "vulnerability" and "adaptation") to better identify feasible adaptation options for food systems. In the 2nd EU SCAR Foresight Exercise, efforts were directed towards a wider resilience perspective beyond the narrow view of food security, changing attitudes to risk, and privileging diversification over specialization. The TRANSMANGO project takes into account the new unfolding conditions and the vulnerabilities of European food systems vis-à-vis future shocks and stresses, and how these may affect food and nutrition security focusing on the diversity of local situations within the EU and within regions. The Metrics of Sustainable Diets and Food Systems initiative adopted the theories of vulnerability and resilience to study and model the sustainability of food systems and to guide the identification of a set of indicators. Because of the SES scientific approach, the geographical analyses of the food system are carried out at a regional level.

3.2 Contribution of vulnerability and resilience theories to sustainability analyses

The conceptual relationship between the vulnerability/resilience framework and sustainability remained often unclear. There is, however, a strong orientation of the applications of SES frameworks, and vulnerability and resilience theories in particular, towards sustainable development interventions. Since Turner et al. (2003), a strong effort has been made to encourage the consideration of vulnerability and resilience research in sustainability science.[4]

3.2.1 SES frameworks for sustainable development

Various frameworks have been developed aiming at defining a common language, framing research and guidance towards sustainable development of SES (Gallopín et al. 2001; Holling and Allen 2002; Turner et al. 2003; Ostrom 2007), and the SES frameworks variables have been key in identifying sustainable outcomes in natural resource management. The variables selected through the SES frameworks explain the dynamics and the interactions in the social and ecological systems, and the framework also provides further variables for exploring the potential sustainable development and management strategies of a social–ecological system (Binder et al. 2013; Schlüter et al. 2014). This type of framework proved suitable for the analysis of complex social–ecological issues that consist of dynamic interactions and for defining the characteristics, activities and dynamic factors of the system leading to or impeding sustainable management (Binder et al. 2013).

Schröter et al. (2005) and Yu et al. (2012) highlighted the link between the common goals of sustainability science and global change vulnerability assessment.

[4] According to Redman (2014), "Sustainability science seeks to address the major challenges facing society while ensuring that human well-being is undiminished and the basic Earth systems continue to operate".

According to these scholars, and consistently with Kates et al. (2001), Clark and Dickson (2003) and Adger et al. (2005), for both those goals, suitability, efficacy, equity and legitimacy in terms of sustainability of development pathways and resilience interventions must be taken into account as we move into an uncertain future. Indeed, the concepts of resilience and adaptive capacity are often associated with sustainability (Conway 1985; Strunz 2012). These notions, together with concepts of vulnerability, have been applied in interdisciplinary research and broadly developed as proxies for sustainable strategies (Turner 2010), through the hypothesis that a broadly resilient but slightly vulnerable and strongly adaptable system could maintain its functions over time (Callo-Concha 2014). In addition, Pretty (2008) and Schewenius et al. (2014) describe how sustainability in agricultural systems integrates the concepts of resilience and persistence (the abilities of a system to buffer disturbance and change and to continue over long periods) while focusing on wider economic, social and environmental outcomes (Holling 1973; Folke 2010; Chelleri and Olazabal 2012; Elmqvist et al. 2013). This perspective is the key to extrapolating useful information from the study of occurring trends and phenomena, to reducing impact and to a system pathways approach in the analysis of sustainability (Callo-Concha 2014). Sustainability, in fact, focuses on pressures affecting the perpetuation of life support systems and provides practitioners and decision-makers with understanding of these disturbances, their implications and the ability of the system to cope with them (Turner 2010). More specifically, Redman (2014) proposed some valuable elements to clearly distinguish and put into relation sustainability and resilience approaches; building on the normative feature and anticipatory goals of the sustainability approach, and acknowledging the non-predictive and adaptive efforts vis-à-vis shocks and stressors of the resilience approach, the author proposes to consider sustainability as the approach that prioritizes fixed outcomes and resilience as the one prioritizing the processes to apply. Thus, in order to identify sustainable solutions to problems in world agrofood systems, it is considered fundamental to explore resilience opportunities and account for the dynamic uncertainty represented by a set of key drivers of change (Thompson and Scoones 2009).

3.2.2 Operationalizing vulnerability and resilience for a system analysis

Within the SES analysis, the theories of vulnerability and resilience have proved a useful framework for understanding the dynamic interconnectedness between humans and the environment and have offered models for improving society's capacity to deal with global change. The main goal of assessing resilience is to pinpoint vulnerabilities in social–ecological systems (Berkes et al. 2003). Such knowledge is crucial for implementing sustainable management strategies and actions (Rammel et al. 2007; Cabell and Oelofse 2012). Nevertheless, there remains a need for further understanding of the dynamics of sustainability of SESs (Carpenter et al. 2009; Schlüter et al. 2014) and for a more rounded and complete comprehension of global change and food security from a social and sustainability science perspective. These further elucidations are required in order to accurately assess the vulnerability of food systems and then to design the socio-economic and political strategies for their adaptation (Yu et al. 2012).

However, resilience and vulnerability are problematic to operationalize through precise assessment methods (Cummins et al. 2005) due to their theoretical and multidimensional nature (Cabell and Oelofse 2012). Scoones et al. (2007) underline that system functions have to be sustained in the face of vulnerabilities occurring at different spatial and temporal scales and suggest that there are four necessary but individually insufficient properties that define the sustainability of a system: stability, durability, resilience and robustness. Stave and Kopainsky (2014) propose, in system dynamics terms, to describe the resilience of a food system, or a simple food system unit, through an analysis of the stocks, building on the hypothesis that any given stock might be sustainable if the flows in and out of the stock are the same. This approach would allow observation of how different conditions of sustainability might have different consequences on the resilience of the system, with respect to its abilities to cope with change through the available socio-economic, environmental and institutional assets.

In order to structure the vulnerability and resilience analysis of the social–ecological system towards a more sustainable future, Cabell and Oelofse (2012) consider that it is first necessary to identify the limits of the focal system (Carpenter et al. 2011) that can be designed through biophysical factors, political frontiers and cultural aspects. In fact, each specific system is integrated within other systems across different spatial and temporal tiers. The regional level is considered an important level for food security, food system research and global environmental change considerations. The subglobal or subcontinental geographical regions scale is a natural level for studies of social–ecological systems (such as food systems) since they are generally defined by common cultural, political, economic and biogeographical contexts. Furthermore, research at regional scale can deliver a set of assets to practitioners, researchers, policy-makers, natural resource managers and other stakeholders for focusing the attention on global change and food security (Liverman and Ingram

2010). Although regions are not always clearly homogenous for socio-economic and biophysical aspects, it is necessary to draw artificial boundaries to define a study area before any vulnerability and resilience assessment can be carried out (Schröter et al. 2005). Thus, considering that vulnerability is extremely context specific (Fraser 2007; Cordell and Neset 2014), and that global change is manifest through subglobal or regional driving forces, cross-scale trade-offs need to be identified.

3.2.3 Assessing vulnerability to sustainability problems

Starting from the analytical approach of vulnerability and resilience in relation to global environmental change, but specifically working on phosphorus resource vulnerability, Cordell and Neset (2014) define a set of several attributes that are necessary to assess vulnerability to sustainability problems,[5] such as integration and inclusiveness of and within coupled human–environment systems; record of complexity of interacting stressors and nested scales; participation of relevant stakeholders; assessment over time for current and future vulnerabilities; study of solutions-oriented adaptation and system resilience strategies; and policy relevance.

Several scholars have proposed different approaches for measuring resilience, spanning from measuring context-dependent proxies of resilience for each SES (Bennett et al. 2005; Carpenter et al. 2006) to more quantified approaches such as mathematical models (Fletcher et al. 2006) and also building more conceptual models of SES (Resilience Alliance 2010). However, it has been proven necessary to follow a stepwise approach to describing the SES in question by first defining its boundaries, framing key issues and driving forces, and identifying critical thresholds (Cabell and Oelofse 2012), referring to a question that was first asked by Carpenter et al. (2001) "the resilience of what to what". Two considerable efforts have sought to provide a "rule of thumb" through defining a common methodological process for the assessment of vulnerability and resilience: Schröter et al. "An eight step method for global change vulnerability assessments" (2005) and Cordell and Neset "Six-step phosphorus vulnerability assessment framework" (2014).

Despite vulnerability and resilience theories proving to be crucial in the investigations of complex social–ecological systems (Leach 2008), there remains a need for appropriate metrics in order to measure the conditions of the system and the stages that have been aimed towards resilience, something that could be achieved through developing a more flexible process of identification of indicators and proxies (Cabell and Oelofse 2012). The indicator approach is the most common method adopted for quantifying vulnerability in the global change community (Gbetibouo et al. 2010). More specifically, Leichenko and O'Brien (2002) highlighted the opportunity to capture the multidimensionality of vulnerability in a comprehensible form through composite indices. Vulnerability indicators are necessary for practical decision-making processes not only to provide policy-makers with appropriate information for the identification of zones of vulnerability, but also to improve their understanding and knowledge of action on the causal mechanisms that are underneath the sustainability of the food systems and that emerge through a vulnerability and resilience analysis (Prosperi et al. 2014). Also, indicators represent one approach to making theoretical concepts—such as vulnerability and resilience, operational, as it has been shown in the indicator-based causal models proposed by Gbetibouo et al. (2010) and Nazari et al. (2015)—and help develop a better understanding of the socio-economic and biophysical factors contributing to vulnerability (Hebb and Mortsch 2007).

Moreover, there is a growing acknowledgement that the impact of food security research on decision-making needs to be strengthened, and the social–ecological systems science approach is considered as the most comprehensive in supporting decision-makers in consolidating the broad sets of interplaying stressors in order to define all-encompassing resilience solutions (Vermeulen et al. 2013; Vervoort et al. 2014). The increasing complexity of food systems is also believed to play a significant role in issues leading to famine and hunger, and an analysis focusing on system dynamics, interactions, feedbacks and nonlinear relationships could contribute to identifying resilience pathways (Ramalingam et al. 2008, Thompson and Scoones 2009; Gerber 2014). Vulnerability and resilience theories, however, are not normative concepts (Adger 2006), and they therefore need to be used and integrated conjointly with other normative concepts, in order to create a constructive dialogue with policy-makers (Leach 2008; Plummer 2010). Still, Hodbod and Eakin (2015) highlight the need to distinguish the conceptualizations of resilience in social–ecological systems from the understanding of resilience of food systems; building on analysis and examples from the 2013–2015 drought experienced in California, the authors show how the structural normative nature of food systems—with the undeniable goal of guaranteeing human sustenance through avoiding disturbances, improving stability and maintaining food security—can bring rigidity to the food system and lessen its adaptability to change. Since food systems are *human-designed* social–ecological systems, social elements are far more controlled than ecological ones. Then, efforts are deemed necessary to use the concept of resilience to foster food security in a more

[5] Sustainability problems can be identified as climate change, natural resources depletion, peak oil, market and political instability, etc.

equitable food system through improving the multifunctionality of food systems at multiple scales, by leaving further room for socio-cultural and biophysical functions, and not only for economic and profit maximization functions that tend to limiting the core focus of food systems and reducing their functional cross-scale redundancy (Hodbod and Eakin 2015). Furthermore, it is the key to consider power dynamics across scales within the contextual community by identifying the focus and the specific goal of a vulnerability/resilience assessment; it is in fact proposed by Quinlan et al. (2015) to improve the suitability evaluation approach of a resilience assessment by answering the questions: "Resilience of what? To what? For whom? And for what purpose?".

Innovative and appropriate approaches to analysis and assessment should still focus on the complexity of food systems and their entangled and multidimensional nature (Foran et al. 2014). For unravelling essential problems in the analysis of social–ecological systems, inter- and transdisciplinary research is largely deemed as extremely helpful (Carpenter et al. 2009; Hammond and Dubé 2012; Ostrom 2009; MEA 2005, Liu et al. 2007, Huber et al. 2013), especially in terms of assessment of wide sets of potential outcomes, agreement between multiple stakeholders with different goals and intervention pathways, and modelling complex dynamics across the different tiers of food systems. Various qualitative and quantitative methodologies can be implemented and integrated in hybrid frameworks using data and information on previous experiences in order to seize system complexity and identify synergies and trade-offs for decision-making (Ericksen et al. 2009; Anderies and Janssen 2013; Prosperi and Peri 2014; Saldarriaga et al. 2014).

Despite numerous valuable efforts, most applications of the social–ecological systems frameworks still belong to the scientific community, while development practitioners' interest for this framework might be inhibited by its system orientation and problems with agency that may not be adequately developed or studied (Foran et al. 2014). Frameworks, theories and models are the elementary units that the scientific community applies to developing, proving and adjusting knowledge, and, through an integrative approach, they are fundamental for creating common languages, answering questions about mechanisms of a system at various scales and under changing states (Epstein et al. 2013).

Although dynamic models are strongly proposed as suitable tools to explore social–ecological interactions, it still remains extremely challenging because of the complexity of the systems studied and the integration and development of knowledge, theories and approaches from different disciplines (Schlüter et al. 2014). Attempts of integration of different frameworks for analysing social and ecological systems have been proposed. For example, Prosperi et al. (2014) attempt to integrate the vulnerability framework into the application of the SES frameworks for the food system, and also, alternatively, Loring et al. (2013) propose to integrate the water–food–energy nexus into a diagnostic application of the SES frameworks.

4 Conclusion

Understanding of the food systems as social–ecological systems can provide concepts to pinpoint the sustainability problems that affect food systems. Food and nutrition security is considered the principal outcome of any food system and relies on the successful completion of diverse activities within the food system (Ingram et al. 2010). These various elements of the food systems are impacted by, and in return impact upon, the socio-economic and environmental conditions of the system across multiple scales. These interactions bring with themselves high uncertainties that can be explored through a vulnerability and resilience analysis. A food system can be vulnerable, or resilient, to a set of stressors (Adger 2006) such as environmental pressures, socio-economic instabilities and institutional and policy factors, and its vulnerability can be defined and observed through exposure, sensitivity and adaptive capacity (Turner et al. 2003; Ericksen et al. 2010).

Scientific analyses of contexts, systems and their properties inform the political process on how to achieve sustainability, and diversification of knowledge, integration of methods and inclusiveness in decision-making and governance are key (Scoones et al. 2007). For the food system, the potential answers can be found in the analyses of the quantitative nexuses between diets, the environment and human health, through the contribution of nutritionists, agriculturists, public health professionals, educators, policy-makers and the food industry sector (Tilman and Clark 2014). In such a dynamic scenario, measures of food and nutrition security that only focus on outcomes, such as hunger and malnourishment, might be too narrow for a comprehensive understanding of the food system and its changing causal mechanisms. However, there are presently no precise and reliable global common metrics in use to measure the sustainability of food systems (Vinceti et al. 2013). It is then key to answer the call for multidisciplinary and more inclusive, social–ecological, system-oriented approaches that look at the resources (financial, physical, natural and social) to capture the dynamic processes between and within the food system activities, nutrition and health, and environmental outcomes.

A large multidisciplinary community of scholars has now built a coherent theoretical corpus around SES frameworks (Ostrom 2009; Epstein et al. 2013). Theories of vulnerability and resilience within the wider context of social–ecological system frameworks have proven helpful in several investigations to understand the complex dynamics involving socio-economic and biophysical aspects (especially in ecosystem management) and in designing sustainable development strategies (Foran et al. 2014; Binder et al. 2013). Vulnerability and resilience theories operationalize a causal pathway that identifies the variables instrumental in ensuring the sustainability of the food system's outcomes. A set of indicators can then be selected to proxy these variables. Through a review of some conceptual approaches linking issues related to food security and sustainable development, it is therefore argued here that vulnerability and resilience can provide the conceptual framework needed to model the complex relationships between food and nutrition security and sustainability and help identify potential indicators of sustainable diets and food systems.

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