UNIVERSITÁ DEGLI STUDI DI CATANIA

Dipartimento di Gestione dei Sistemi Agroalimentari e Ambientali

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Tesi di Dottorato di Ricerca in "Economia Agroalimentare"

XXVI ciclo

PAOLO PROSPERI

Metrics of food security and sustainability
An indicator-based vulnerability and resilience approach

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Chapter 1

Introductory chapter.

Sustainability of food systems: A Social-Ecological Systems Frameworks perspective

1.1 - Background

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 are chronically undernourished (FAO, IFAD, WFP, 2014). Concurrently, nearly 2.1 billion people are affected by malnourishment related to unhealthy food consumption and dietary trends, which is reflected in the spread of food-related diseases like obesity and nutrient deficiency (Ng et al., 2014). At the same time food production and consumption exert a huge impact on the environment and are significant sources of green house gases. Furthermore, agriculture is responsible for 70% of water withdrawal (FAOSTAT, 2012) and represents a main driver of deforestation and loss of biodiversity. Food systems rely on physical resources such as land, water, biodiversity, and fossil fuels which are becoming ever more fragile and scarce. 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).

Food insecurity is a persisting global issue and the food system is now facing a new set of intersecting social, environmental, and economic challenges. Food security depends essentially on ecosystems and their services and during the last 50 years the physical and functional availability of ecosystem services has fallen faster than ever before (IAASTD, 2009). Presently Earth's life support systems encounter a condition of serious depletion and human development will be confronted with rising resource shortage (MA, 2005).

The leading tenet related to food insecurity issues focuses on improving access to adequate food for those who suffer from hunger and malnutrition, and on increasing supply by 70–100% - through agricultural intensification – in order to feed a growing human population confronted with rising incomes, urban transition and changing dietary preferences (FAO, 2009; Foran et al., 2014). A number of common policy strategies have been encouraged to foster sustainable food security and consist mainly of closing yield gaps, improving resource efficiency and production limits, changing consumption trends, banning agricultural expansion and cutting waste (Godfray et al. 2010; Foley et al. 2011).

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). Evidences related to this global change are observed through worldwide-reduced yields that are severely affecting food security (Lobell et al., 2011). Besides environmental change, numerous socio-economic factors bear critical responsibilities in food systems and drive outcomes of food security (Ericksen, 2007).

Food and nutrition security as main outcome of an integrated food system

"Food Security" was defined - in the 1996 World Food Summit (United Nations) - as the state that "*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*". 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, social welfare and environmental capital. Furthermore, various elements of food systems are altered by, and actively impact, the socioeconomic and environmental conditions of the system across local, regional and global levels. These interactions are featured by - and bring with themselves high uncertainties (Ericksen, 2008; Ingram et al., 2010; Ingram, 2011) (Figure 1).

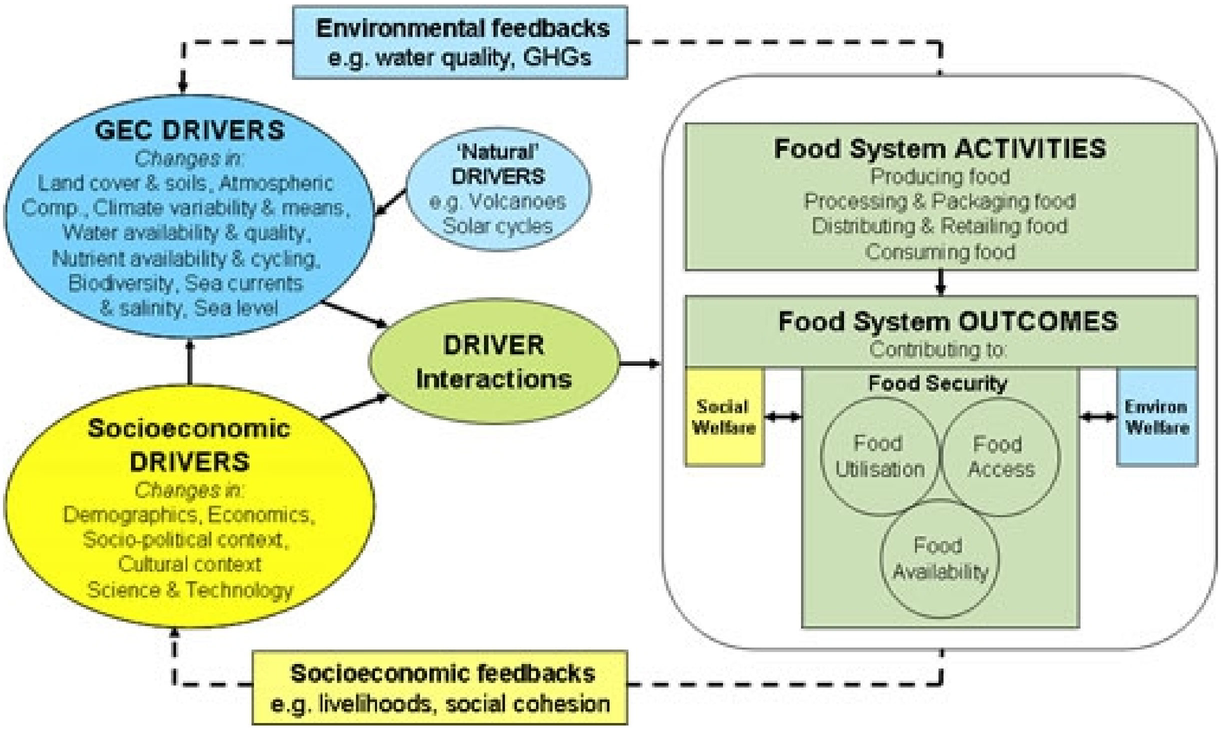

Figure 1 - Food system framework (Ericksen, 2008)

Food and nutrition security then is considered the principal outcome of any food system (Ericksen, 2010) and is a multidimensional concept that can be analyzed at individual, household, community, national, regional and global level (Ingram, 2011). Fulfilling the food demand remains challenging because of the disturbances brought by global environmental change. 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). 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 Ericksen (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 socioeconomic and global environmental change drivers (Gerber, 2014). Thus, food systems are considered social-ecological systems that comprise biophysical and social factors linked through feedback mechanisms (Berkes et al., 2003; Ericksen, 2008) (Figure 1). Food insecurity, therefore, arises when multiple biophysical, economic and social stresses (strongly linked to global environmental change) negatively impact, individually or concurrently, on different aspects of the food system (Ingram et al., 2013; Ericksen, 2014). These multiple pressures converge on the major determinants of food security, namely supply, access and utilization (Misselhorn et al., 2012).

Global food security is facing several challenges, and there are key elements that might support a successful food system. The global food system is changing fast and in the meantime is being confronted with surrounding global socio-political and ecological changes (Cabell and Oelofse, 2012), however, human societies have the ability to anticipate and modify these changing trends (Holling, 2001).

Together with global environmental change, increasing economic and social inequalities, market and political instability, and shifting consumption patterns hamper the global food system, with consequences such as the double burden of malnutrition (Garrett and Ruel, 2003). Depletion of ecosystem services, the loss of freshwater resources and soil erosion contribute to further threaten the capacity of humans to fulfill their nutritional needs (MA, 2005; Carpenter et al., 2006; McIntyre et al., 209). 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 (Gliessman, 2007; Ericksen, 2008 GEC; Cabell and Oelofse; 2012). These evidences show the crucial contradictions and challenges that the food system is facing. 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.

Generally, agricultural and resource management problems are categorized as classic system problems. Similarly to food systems, aspects of systems behavior are complex and difficult to anticipate and causes are multiple. In natural and social systems, and their interplays, problems are often non-linear, dynamic, and cross-level in time and space. It is thus necessary to have one system-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 (Ericksen, 2006; Thompson et al., 2007). Since systems approaches focus on the dynamic interactions among different components, they are necessary for understanding the non-linear mechanisms through which global environmental change impacts not only on agricultural production but also on economic, cultural, and other factors (Ericksen, 2014).

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 & Clark, 2014). In such a dynamic scenario, measures of food and nutrition security that only focus on hunger and malnourishment might be too narrow for a comprehensive understanding of the food system and its changing 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). 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 (Allen et al., 2014).

1.2 - Social-Ecological Systems Frameworks

Foran et al. (2014) comprehensively synthetize what is generally intended by the term ‘Social-Ecological System’ (SES): "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". SESs are dynamic systems that are continuously changing in response to internal or external pressures (Berkes and Folke 1998; Schluter, 2014) and the literature concerned was initially oriented mostly towards environmental change and the medium- and long-term impacts of human activities on future human prosperity (Foran et al., 214). Furthermore, most complex phenomena involving concurrently social and ecological systems are indivisible and any differentiation is thus considered counterfeit and subjective (Berkes and Folke 1998). SESs involve societal-human and ecological-biophysical subsystems in mutual interaction (Gallopín 2006).

Food system as a Social-Ecological System

Food systems are a form of complex social-ecological system (Allen et al., 2014) spanning the biological and socioeconomic 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) picked 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 the 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. The SES frameworks arise as system-oriented frameworks that give further priority to complexity, analysis of systemic interactions and problem identification (Foran et al. 2014). In addition, from this analysis it is possible to observe that the SES frameworks appear to further emphasize the understanding of the relationships and the behavioral conditions of food systems faced with global change.

Alternatively, Binder et al. (2013) compared ten established conceptual frameworks that are meant to analyze 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, however, with regards to contextual and structural criteria, 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 throughout their contextual and structural characteristics into four groups: Ecocentric, Integrative, Policy and Vulnerability frameworks. The SES framework is thus considered an Integrative Framework since, consistently with Foran et al. (2014), it deems the mutuality between the social and the ecological systems and comprehends various types of feedbacks loops within the social system and between the social and ecological systems in different time scales. Significantly, as demonstrated 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 to tie together disciplinary and methodological bounds (Epstein et al., 2013). For several years now a vast community of scholars has gathered knowledge to make the SES framework a common classificatory framework for enhancing the understanding of complex social-ecological systems through multidisciplinary efforts (Ostrom 2009; Epstein et al., 2013). In fact, the SES framework approach is widely considered as unique in its treatment of social and ecological systems in equal depth and its ability to offer a structure for developing several levels of specificity by discerning diverse tiers (Binder et al 2013).

Initially the SES framework originates from literature on ecosystem management and ecology and has strongly 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 it has been usefully applied to food systems (Ericksen, 2007; Ingram et al., 2010).

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 sub-systems (Ingram et al., 2010; Foran et al., 2014). Several investigations, from different discipline perspectives, were led on food and nutrition security through the lens of vulnerability. Socioeconomic studies find the causes of vulnerability, at both the level of the individual and at various group levels, mainly in socioeconomic 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 (Ericksen et al., 2009; Eakin, 2010; Ingram, 2011; Misselhorn et al., 2010).

Defining vulnerability and resilience of a food system

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, 2007; Conway and Barbier, 1990; 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 addition Berkes et al. (2003) and Gunderson and Holling (2002) find that shocks and perturbations potentially represent opportunities for innovation and transformation. On the other hand, a food system is considered vulnerable when it fails in delivering one ore many of its intended outcomes, because of even small stresses that might bring to significant social-ecological consequences (Adger, 2006; Ericksen 2008a; Ericksen, 2008b; Eakin, 2010).

Vulnerability - as the propensity or predisposition to be adversely affected (IPCC, 2014) - of a food system is a function of exposure, sensitivity and adaptive capacity (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, socioeconomic instabilities and institutional and policy factors (Figure 2).

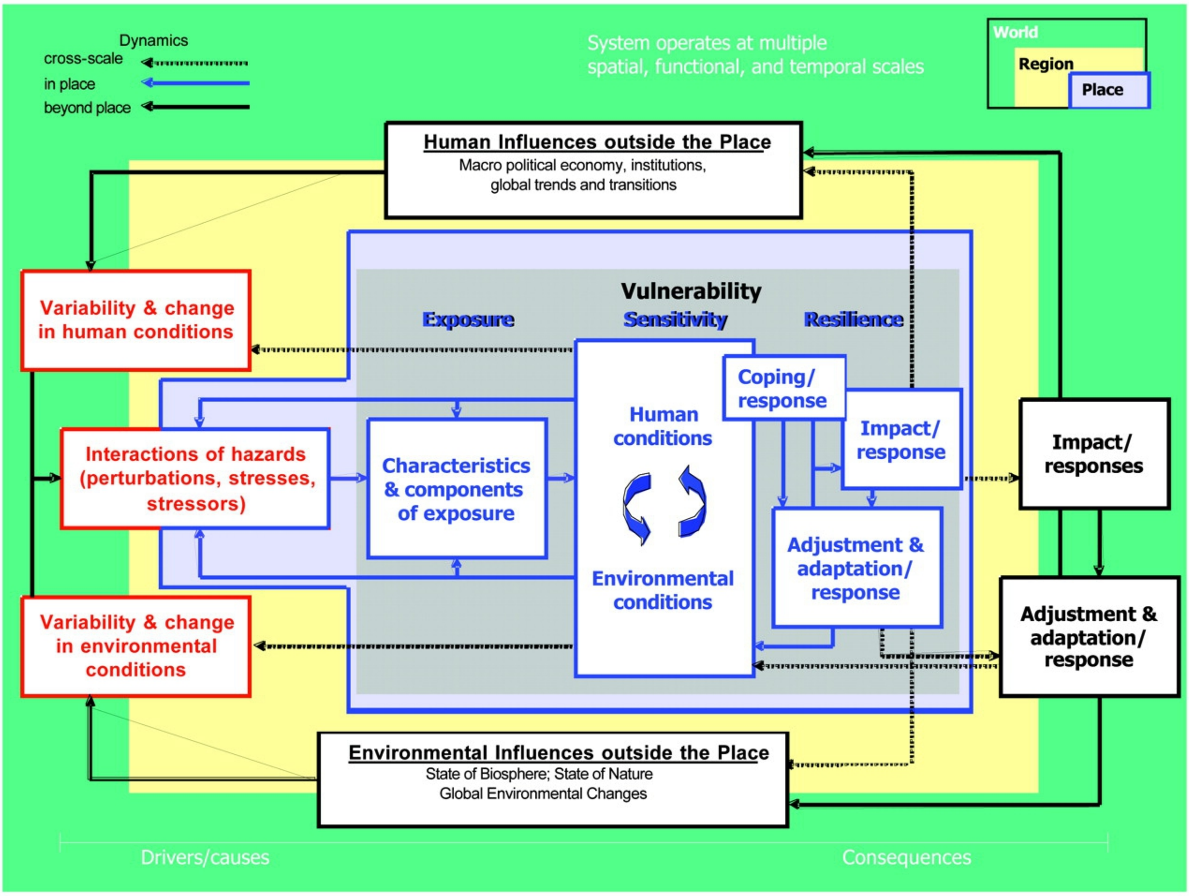

Figure 2 - Vulnerability framework (Turner et al, 2003)

Therefore 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, livelihoods security, sustainability science and risk and resilience (Adger, 2006; Fussel, 2007; Cordell & Neset, 2014). Vulnerability assessment belongs generally to a context and an area of study defined by natural or artificial boundaries (Downing and Patwardhan, 2005; Schroeter et al., 2005) (Figure 2). Except for broad assessments of vulnerability to global environmental change (Rockstrom et al., 2009), climate change vulnerability is generally analyzed 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 (Cordell & Neset, 2014).

Resilience, closely related to vulnerability in social-ecological systems, implies concepts of adaptation, transformation, innovation, self-organization and the capacity to perpetuate the activities over time despite the occurrence of stressors (Adger, 2006; Cutter et al., 2008; Folke, 2006). 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 (Rockstrom, 2003; Adger, 2006; Resilience Alliance, 2010).

Vulnerability of the food system to global change

Contemporary food systems are characteristically cross-level and cross-scale (Liverman et al., 2010), and rely on a large set of biophysical and socioeconomic factors. Food and nutrition insecurity is the final result of a number of interactions between the global environmental change impacts on the food system and various socioeconomic dynamics. The effects of these interactions are observed in given exposed areas or populations. A sustainability perspective and a multidisciplinary analysis help to explore the complex interconnectedness of the economic, social and environmental aspects of the food systems in order to inform decision-making on the critical challenges of food insecurity and strengthen sustainable and resilient livings for present and future generations (Misselhorn et a., 2012).

In recent vulnerability analyses, climate change is one of the most studied topics. Since the early 1990s numbers of scientific studies concerning climate vulnerability have increased regularly over time (Adger and Kelly, 1999; Kelly and Adger, 2000; Klein and Nicholls, 1999; e.g. Tegart et al., 1990). In recent years, investigations have advanced by incorporating social vulnerability to climate change and adaptive capacity (Ericksen et al., 2005; Fussel and Klein, 2006; Parry et al., 2007; Schroeter et al., 2005; (O'Brien et al., 2004; Cordell and Neset, 2014). As mentioned above, the impacts of climate change interplay with 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 (Ericksen et al., 2009). Implementing linear policies becomes difficult in such uncertain dynamic conditions (Funtowicz and Ravetz, 1993, Kriegler et al., 2012 and van der Sluijs, 2005; Vervoort et al., 2014).

From a social-ecological systems perspective where the simultaneous occurrence of several nature- and human-related drivers of change (such as climate change, natural resources depletion, habitat loss and pollution, shifting dietary patterns, financial speculation on food commodities, and oil extraction) threaten the ability of a global food system to maintain its vital functions and processes, food security is a global scale issue, from the North to the South (Brunori and Guarino, 2010; Allen et al., 2014). The drivers of change affecting the food system can be identified in five main categories, namely: environmental, economic, social, technological and political (SCAR, 2009).

Despite the importance of the various specific interactions between a number of global and regional drivers of change and context-related food and nutrition security issues, it is still necessary to stress the role of climate change as main environmental driver of global change that affects agricultural production and food security through unattended biophysical shocks (European Commission, 2011). Global environmental change implies transformations in the physical and biogeochemical environment from both natural and human origins such as deforestation, fossil fuel consumption, urbanization, land fill, agricultural intensification, freshwater withdrawal, fisheries exploitation and waste production (Liverman and Kalapadia, 2010). Greenhouse gas (GHG) emissions and changes in land use, engendered by food system activities, strongly contribute to climate change, however these activities appear responsible for other aspects of global environmental change as well such as alteration of freshwater quality and supply, biodiversity, land cover and soils, nutrient cycling and air quality (Ingram et al., 2010). At a regional level it has been shown that climate change strongly contributes to major environmental concerns such as desertification, water stress, biodiversity loss, and soil degradation in the European Mediterranean area (Van Ittersum and Rijk, 2009).

Furthermore, GHG emissions directly affect temperature, freshwater availability and numerous parameters of climate change (Wood et al. in Ingram et al., 2010). 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. in Ingram et al., 2010).

With specific regards to the food system human activities, the rate of agricultural land-use expansion over the last 60 years has substantially degraded biodiversity, topsoil, forests and water-quality (MA, 2005). Increasing water shortages and extreme weather events are associated with yield reduction and instability, and a decrease in areas suitable for traditional crops (Olesen, 2006; Olesen & Bindi, 2002), phenomenon that as been reported likely to occur in the European Mediterranean region (Schröter et al., 2005a; 2005b; Metzger et al., 2006).
Both climate and non-climate drivers affect food systems. For instance, non-climate drivers such as urbanization and pollution, and other socio-economic processes (including land-management change) directly and indirectly influence social-ecological systems (IPCC, 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 influence many food-related context-specific practices (Oosterveer and Sonnenfeld, 2010).

Almost all food systems in a global food system threaten the ability of Earth to provide food in the future. For this reason these food systems are not considered to be sustainable. Food production in Europe is closely outstripping the regional and global environmental breaking points, particularly with regards to nitrogen synthesis, phosphorus use, land use and degradation, and the dependence on fossil energy. Within the same context, agriculture and fisheries are the largest drivers of biodiversity loss and water extraction (SCAR, 2011). These critical environmental outcomes reveal that the future of food availability is closely related to the society's capacities in providing appropriate technologies and practices to sustain the productivity of the natural assets and compensate the ecosystem services degradation (Eakin et al., 2010). Broadly considering that the exacerbation of the habitat loss has effects on poverty, international trade, finance and investments, and political equilibriums makes evident that this change jeopardizes not only food supply but also global stability and human development. Then, sufficient and nutritious food will be less affordable for disadvantaged groups of the population because of the concurrent occurrence of price volatility, interconnectedness of global commodity markets, increasing pressure of climate change on food production and loss of biodiversity (SCAR, 2011). The 2007-2008 food crisis demonstrated the complex interlinkages of the food system with environmental, financial and energy crises, calling for interventions of mitigation (SCAR, 2009).

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. This phenomena and perturbations are not entirely controllable or predictable. (Ericksen, 2008 E&S; 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 towards the achievement of the food security outcomes (availability, access, utilization), and these activities are consecutively altered by several factors (Ziervogel and Ericksen, 2010; Bausch et al., 2014). Therefore, in a complex and adaptive system, for instance the European food system, food security outcomes are not possible to be forecasted 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 socioeconomic, environmental, technological, and global political factors around the food system (Ingram ESF, 2009). Vulnerability and resilience of agri-food systems originate from several sources that interact to engender unpredictable responses, and system thinking is key to account for the interdependencies between drivers, feedback loops and non-linear trends (SCAR, 2009).

Food security and development practitioners work towards food security trying not to further compromise environmental and social welfares. Nevertheless they risk undermining ecosystem services through increasing the efficiency of food production (MA, 2005; UNEP-IWMI, 2011). The aim thus is to build resilient food systems, achieving food security and trying to maintain desirable ecosystem states and services, despite global environmental pressures (Folke et al. 2002; Gunderson & Holling,2002; Walker et al., 2006). To answer this necessity is key to close the gap in the understanding on the interactions among food security, vulnerability, resilience, and ecosystem services (Ericksen et al., 2008).

1.3 - Pertinence of the SES framework to the analysis of properties and interplays within contemporary food systems

The principal outcome of any food system is food and nutrition security. In particular food and nutrition security comprises the three components of availability, access and utilization. Food availability, or supply, is the amount, type and quality of food that a unit gets to consume. The access to food consists of the ability to acquire appropriate food and can be analyzed in terms of affordability, allocation and whether consumers can meet their food preferences. The utilization of food refers to the ability to consume and benefit from food (Ericksen et al., 2010). Nutritional security fully integrates this definition of food security since the available and accessible food has to be nutritious. The fulfillment of such food demand is jeopardized by global environmental change including climate, biodiversity, water availability, land use, tropospheric ozone and other pollutants, and sea level rise (Foresight UK 2011; GECAFS, 2005; Gregory and Ingram, 2000). As described above, these biophysical changes are generated also through food system activities and feedbacks on the environment that are further intensified by the coexistence of Global Environment Change (GEC) with competition for natural resources (Molony and Smith, 2010; Misselhorn et al., 2012; Ingram, 2011). For many years now various research studies have considered, from different perspectives, the vulnerability and resilience frameworks as some appropriate methodologies to find solutions to food security problems (Alwang et al., 2001). These principles are still regarded as key to reconsider social research and social intervention policy approaches to food security (Brunori and Guarino, 2010).

"Food security can only come from making food systems sustainable" (Lang, 2010 book). To assess the sustainability of the food system - i.e. its capacity to maintain its essential functions/services over time (Conway, 1985) (food and nutrition security being its principal outcome) - we need to understand what might affect its processes, to what extent the drivers of change (such as forces likely to affect the structure and the functions of a system) impact the food system outcomes (such as the activities along the value chains), and how actors respond to these pressures. Food security is at risk of an increasing number of dynamic constraints and drivers of change, and its multiple dimensions need to be holistically and systematically considered faced with these new challenges (SCAR, 2009). Thus, a food system, together with its functions, is considered vulnerable to one or more stressors (such as economic shock, institutional instability, environmental change etc.) when it is not able to sustain food security (Ericksen 2008 E&S).

Building on Eakin (2010), the whole food system is here conceptualized as a vulnerable entity and specific vulnerabilities are explored through analysis of the characteristic food system outcomes. Thus the "what is vulnerable" is identified in the capacity of a specific entity, providing ecological and social services, that is composed of a number of actors, activities and processes acting against the global drivers of change. The functions of the system will be considered vulnerable if negative food system-outcomes will emerge (Eakin 2010 in Ingram et al., 2010). For instance the current joint crisis of malnutrition and unsustainability originates from agricultural and food systems that do not provide sufficient essential nutrients for dietary requirements of people (Allen et al., 2014; Graham et al., 2007; Declerck et al., 2011). As supported by a recent paper whose title literally states "Vulnerability of Food Security to Global Change" (Ericksen, 2014), we refer to the analysis of vulnerability and resilience, of an issue of the system, to a critical driver of change, with the aim of assessing the potential of the system to maintain its activity over time, and thus the likelihood of the sustainability of the system. Ericksen (2008) suggests that vulnerability and resilience are inherent properties of the processes and activities of food systems, and also determine the responses to external and internal stressors occurring over time. This analysis would help to elucidate how vulnerability is manifest in a food system, finding and anticipating the characteristic of the potential vulnerability and the adaptive behavior. One key conceptual element is a clear distinction between causal events and outcomes (Dilley & Boudreau, 2001); a "causal factor approach" that describes the interactions leading to the final outcomes. This would allow a dynamic analysis of the particular issues of vulnerability, instead of a static identification of vulnerability to a broad and general final outcome (Prosperi et al., 2014). A broad understanding of vulnerability on a wide range of sectors or issues would not be sufficiently focused to implement actions (Eakin & Luers, 2006; Ionescu, Klein, Hinkel, Kumar, & Klein, 2009; Luers, 2005). There is then a rising call for new types of systems analysis and modeling tools (Nicholson et al., 2009).

The integrated fragmentation of the broad vulnerability into specific vulnerabilities represents a response to the lack of causal factor analyses. Developing and applying this approach could provide empirical evidence contributing to a better understanding of the behavioral aspects of the food system (Ericksen, 2008 E&S). This approach has already been used to elucidate dynamic feedback mechanisms characteristic of the food system providing a more detailed view of the food security issues and demonstrating that the various crises since 2007 (oil, food, financial and economic) were interdependent. This provides the elements for anticipating and changing attitudes to risk (EU SCAR, 2009). In particular, through this approach Ericksen (2008) prompts at describing the impact of environmental change on the food system within a socio-economic and political change, in order to identify the synergistic effects of this plethora of stressors interacting with the food systems and often leading to its vulnerability.

In the following sections a set of stressors, selected from the environmental, economic, social, technology and policy drivers mentioned above (SCAR, 2008), are analyzed (through literature review at European level) for their potential impact on a set of critical aspects of food and nutrition security, including availability, access and utilization issues, in a sort of interplay systemic mechanism that answers the question "what is vulnerable/resilient to what" in food systems.

Issues related to Water depletion

Nutritional quality

The loss of freshwater resources may affect the nutritional quality of food supply through the reduction of the production of specific nutrient-dense foods because of water scarcity, and also through utilization of low quality water sources because of both water shortage (and consequent low dilution) and water contamination. The nutritional characteristics of diets are directly related to environmental conditions (Prosperi et al 2014). In fact agriculture affects health directly through its capacity to deliver a sufficient quantity of nutritious foods to consumers (Dangour et al., 2012; Johnston et al., 2014). The state of greenhouse gas levels impacts rainfall, hampering water availability and quality. In turn, agrofood productivity impacts prices and quantities and hence trade and markets (SCAR, 2009; Wood et al. in Ingram et al., 2010). Current water usage and management are driving toward food shortages. Global food production is increasingly dependent on rain, and climate change is reducing rainfall rates in many parts of the world. Concurrent climate change, increasing demand and higher costs for water and fertilizers exacerbate the vulnerability of the agrofood systems and are affecting poorer consumers (SCAR, 2009). Furthermore, global consumption of food has increased and projected population and socioeconomic growth will double food demand by 2050 (FAO, 2008). It has since been estimated that cereal yields will need to increase by 40% and net irrigation water requirements by 40-50% (SCAR, 2009) to meet this demand. If at international level, competition for water to guarantee the domestic food security of nations is increasing, at a sectorial scale there is a growing competition for water between agriculture, public water supply, industry and energy sectors, suggesting that insecurity in food supply may well become an issue in the future (Brown 2008, Bates et al. 2008; SCAR, 2009).

More specifically, in some areas there is a shift from hydrological surplus to deficit; the 'dilution' capacity of water is reduced, and the concentration of agrochemicals and soil nutrients increases. Furthermore, higher water temperatures will affect water quality and exacerbate many forms of water pollution (eg. sediments, nutrients, pathogens, pesticides, salts) (Bates et al, 2008; SCAR, 2009) that will likely hamper human health through the contamination of agricultural product (PARME, 2010). Moreover, often farmers prefer using pesticides for increasing crop yields without considering the threat to a fundamental ecosystem service such as water resource (Ericksen et al., in Ingram et al., 2010, p.132).

Access to food

Water scarcity and depletion may also affect the economic access to food, for instance through the impact of water pricing on food prices. It is widely acknowledged that GHG impact on precipitation quantity and frequency, affect productivity and in turn affect food availability and its quality (Wood et al. in Ingram et al., 2010). For now, scarcity mechanisms, put in place to control the use of available water, comprise access limitations, either technological, legal or through pricing (SCAR, 2011). It has been shown that increasing water prices (through financial support to guarantee water quantity and integrated river basin management to improve water-use efficiency) inevitably lead to an increase in the cost of agricultural production, and therefore a potential decrease in food affordability (Ingram and Kapadia in Ingram et al., 2010). Regulating water utilization efficiency can have a considerable impact on biological, economic, and nutritional factors (SCAR, 2011). Agrobiodiversity richness can contribute to contrast water scarcity and its indirect impacts, for instance through developing drought-resistant. Also focusing on food import from water rich countries can reduce the impact of water on food prices, whether the price of the external imported virtual water is lower than the internal one (Prosperi et al., 2014).

Issues related to Biodiversity loss

Nutritional quality

The nutritional characteristics of diets are closely interlinked with the state of the environmental capital (Prosperi et al 2014). The loss of biodiversity richness affects the availability of diverse necessary nutrients to food production. Indeed, agricultural production impacts on health directly through its potential in supplying adequate amounts of nutritious foods for consumers (Dangour et al., 2012; Johnston et al., 2014). The quality of nutritional supply and human health is thus in danger because of a loss in biodiversity (Allen et al., 2014). Genetic diversity has declined globally, particularly among cultivated species (MA, 2005) and biodiversity loss has detrimental effects on human nutrition as commonly available foods do not provide the adequate nutritional diversity required for sufficient intake of micronutrients by human beings. In fact, nowadays global food chains are homogenized for processing and delivering few species and varieties. Diversity and local species are neglected (Khoury et al., 2014); three crops alone (rice, wheat and maize) account for more than 55 % of human energy intake (Stamp et al., 2012).

The focus on ecologically simplified farming systems, based on cereals, contributes to micronutrient deficiency, poorly diversified diets, and malnutrition in both developed and non-developed areas (Frison, Smith, Johns, Cherfas, &Eyzaguirre, 2006; Graham et al., 2007; Negin, Remans, Karuti, & Fanzo, 2009; Remans et al., 2011; Welch & Graham, 1999). This increased reliance on domesticated species and selected crop varieties can be linked to a significant reduction in dietary diversity. Agricultural biodiversity is thus considered an essential component in the sustainable delivery of a more secure and nutritious food supply (Allen et al., 2014). Paradoxically the efforts accomplished to guarantee food supply, based on the exploitation of ecological services, hamper the ability of the ecosystems to deliver the essential nutrients for human diets (Palm et al., 2007). Nutritional diversity is now widely recognized to be a key factor for adequate diets likely to satisfy the complex human nutritional needs (Arimond et al., 2010; Roche et al., 2008; Randall et al., 1985; Torheim et al., 2004; Arimond & Ruel, 2004; Pelletier & Frongillo, 2003) (Allen et al., 2014). Recently, it has been evaluated that coastal and marine biodiversity contributes to the nutritional basis of 20 % of the world's population. Its loss represents a major risk of irreversible nutritional damage (SCAR, 2011). Furthermore, loss of agrobiodiversity interacts with other food system stressors and thus makes food systems more vulnerable to climate change and to volatility in prices for energy, water and fertilizer, since globally privileged varieties are usually strongly dependent on external inputs (Brunori et al., 2008). The impact of natural resources depletion and the decline of the recovery potential of the food system, based on the ecosystem services, will significantly shape the future of food and nutrition security (SCAR, 2011).

Plant and livestock genetic diversity is widely acknowledged for contributing to ecosystem services conservation and food and nutrition security issues through, in particular, supporting the viability of agricultural systems and long-term productivity, ecosystem cultural services, pest management, soil water retention and increased nutritional value of foods, vis-à-vis increasing global environmental and natural uncertainties (Thrupp, 2000; Reidsma and Ewert, 2008; Eakin in Ingram et al., 2010; IAASTD, 2009; SCAR, 2011; SCAR, 2009).

Cultural preferences

The loss of biodiversity may affect the satisfaction of cultural food preferences. According to the SCAR Foresight 2011, the loss of agrobiodiversity is considered one of the main drivers (amongst others such as price volatility, access restrictions and the interconnectedness of global commodity markets, as well as the increasing detrimental action of climate change on food production systems) that will make adequate food still more inaccessible to the poor.

Diets are complex combinations of different food items influenced by cultural and regional preferences (de Ruiter et al., 2014). In the agrofood system, it is acknowledged that crop mix is altered by climate change, and that the livelihood of producers and cultural traditions and preferences, which are strictly linked to regional varieties and diets, are at risk (Liverman and Kapadia, in Ingram et al., 2010). Few global crop commodities and food products characterize the human preference for energy-dense foods (Kearney, 2010; Khoury et al., 2013) and the global trend consists of homogenizing food production instead of enhancing and keeping traditional food cultures (Jacques & Jacques, 2012). Habitat depletion and biodiversity loss contribute to reduce the enormous amount of information on nutritional and health benefits of the foods, that shapes the cultural food preferences of people (Kuhnlein et al., 2009). Furthermore, monoculture and lack of diversity push food system failure (Wahlqvist & Meei-Shyuan, 2007). For instance, in public health terms, the worldwide maneuvered trends of human preference for energy-dense foods, built on limited global crop commodities and processed foods, is closely related to the increasing occurrence of non-communicable food-related diseases (Kearney, 2010; Pingali, 2007; van de Wouw et al., 2010; Khoury et al., 2013).

Agrobiodiversity includes a series of social, cultural and ethical variables (Allen et al., 2014). Food intake variety is positively correlated with a sense of personal food security (Wahlqvist, 2003). The decreased food biodiversity, caused by the homogenization of the global diet, could result in the loss of unique and traditional foods (Jacques and Jacques, 2012). For instance several scholars have observed that in remote bush communities, access to traditional foods cannot be met anymore with locally available wild food, and that local populations can only access more expensive food of far lower quality and cultural relevance (Colt et al, 2003; Goldsmith, 2007; Gerlach et al, 2008; Martin et al, 2008; Receveur et al, 1997; Kuhnlein et al, 2004; Ford, 2008; Loring and Gerlach, 2009; Ericksen et al, 2010).

Know-how of preparing a more diverse diet can change consumption of different food products (Johnston et al 2014; Termote et al. 2010) and can provide resilience elements for satisfying cultural food preferences against biodiversity loss. Stimulating consumption habits that are sensitive to the impact of food crop choice on health is now critical (Khoury et al., 2014).

Issues related to Price Volatility

Nutritional quality

Food price volatility may affect the nutritional quality in food supply through direct and indirect impacts such as feedback loops on production due to consumer demand (SCAR, 2009). In particular, trade dynamics have a potential negative impact on food supply, especially in disadvantaged groups (WHO-EU site). The links between productivity, prices and trade, and their impacts on food availability and affordability are widely acknowledged since food system prices, quantities exchanged and trade are closely associated with the state of greenhouse gas levels, temperature, rainfall and other surface climatic parameters that hamper food production (Wood et al. in Ingram et al., 2010). Furthermore, there is a clear link between food prices and oil prices. The reason is that the present agricultural production, trade, processing, distributions and retail systems, and fossil fuels, are tightly coupled systems, and this is an important driver of the vulnerability of food provisioning (DEFRA, 2008; SCAR, 2009). Hence, changes in international trade and agricultural policies can led to profound changes in the composition and availability of food supplies and can significantly affect food prices.

Access to food

The determinants of food affordability involve pricing policy, seasonal and geographical variations in price, ratio between local and external prices, and households' income and wealth levels (Ingram in ESF, 2009). Food price volatility through market disruption may affect the capacity of vulnerable nations and populations to access healthy amounts of food. Price volatility has a considerable effect on food security since it impacts incomes and purchasing power (HLPE, 2011). This is linked to the income and employment conditions of people and also to dominant consumption patterns. Food access depends upon the affordability of adequate food, which itself is based on the income of the people and the prices prevailing in the market. Both of these variables fluctuate from year to year and food price volatility is considered one of the most relevant drivers altering food accessibility for the poor (SCAR 2011). In the context of food systems, prices, trade and productivity impacts are closely related to food affordability and availability (Wood et al. in Ingram et al., 2010). Food prices and food affordability are paramount determinants of food choices, obesity and non-communicable diseases (Lee et al., 2013). Studies carried out during the recent food price inflation have brought into discussion the capacity of certain social groups to access quality food once taken for granted (SCAR, 2009). Increase in food prices is a global trend that affects especially the poorer social groups dependent on salaries and tightly connected to the rest of the economy (Von Braun, 2008). Even in European contexts these increases are likely to hamper access to desired and quality food (UK Cabinet Office, 2008-Food Matters). This phenomenon was manifest in the recent food price inflation (SCAR, 2009) since higher food prices tend to have negative impacts on consumer health directly affecting food intake (quality and quantity of affordable food) (Regmi & Meade, 2014).

Consumers normally attempt to cope with the crisis by modifying shopping strategies, for instance purchasing lower quality foods, as demonstrated by Italian consumers who reduced meat consumption and increased their consumption of pasta (Parise, 2008) whilst also purchasing more of their food from discount grocery stores (Brunori and Guarino, 2010). Alternatively, resilience opportunities can be found in the capacity of shifting towards cheaper or locally available foods while meeting the same caloric and nutritional requirements. Countries can also implement food policies for diversifying supply sources through different strategies such as subsidies, food stamps or promoting diversity in food consumption patterns.

Issues related to trends of food consumption patterns

Nutritional quality

Food consumption patterns and trends have a direct and critical effect on food production patterns and overall food security (UNEP, 2012). In fact, food industry focus is to meet the needs of price and quality for the consumers. In turn, the nutritional characteristics of diets are directly related to environmental conditions, which are consequences of the production system associated with current food consumption patterns (Prosperi et al 2014). Trends in consumption patterns involve the variety of diets, changing habits, the difference in food consumption between the rich and poor, and health gaps within social groups. The consequences of the nutrition transition, characterized by a stronger demand for cereals, simple sugars and an increase of meat consumption in low- and middle-income countries, impact food supply, its quality, and the related pressure on ecosystems, but also production, imports, and prices (SCAR, 2011). These changing habits are also reflected in the consumption of food outside of the home and with increased consumption of industrially-produced highly processed foods with an often higher content in energy and fat (WHO-EU site).

Understanding the determinants of consumer choices can improve agricultural and food systems in delivering nutritious food, as well as the health of the consumer (Allen et al., 2014). A broader scientific understanding is necessary for influencing food choices towards healthier food habits and for informing consumers. At a supply chain level, the food industry and retail sector, as well as the media, play a key role in changing consumer patterns (SCAR, 2011). A food system approach elucidates the interrelation of food production and processing, and food consumption patterns and nutritional outcomes (Schubert et al., 2010).

Dietary balance

Dietary energy balance is hampered by the shift towards particular food consumption and dominant lifestyles (increase in fats and sugars, decrease in plant proteins). These changes lead, as causal factors, to obesity and cardiovascular and nutrition-related non-communicable diseases such as heart disease, cancer, overweight and diabetes (PARME, 2011), with the latter tripling in some developing countries (UNEP, 2012). This trend towards industrially produced products and away from traditional foods is defined as "nutrition transition" (Kuhnlein et al, 2004; Popkin and Gordon-Larsen, 2004), and comes at great economic, physical and psychosocial expense (Ingram et al., 2010). It is now widely assumed that the nutritional transition, allied to more sedentary lifestyles, is also driving obesity (SCAR, 2009). Changes in global social systems are key as well in influencing diets through issues related to household livelihood and income and world population dynamics (Mendez and Popkin, 2004; Monteiro et al., 2004; Hawkes et al., 2009). Nutrition transition moving towards diets of highly processed foods and animal products with high levels of saturated fats is now developing rapidly in middle- and low-income countries, changing the face of food consumption (Popkin, 2002; Friel and Lichacz, 2010). In the meantime, especially in the developed world, a disproportionate consumption of meat, dairy products and processed foods is generating a rapid increase of food-related health problems, such as obesity and diabetes (Liverman and Kapadia, in Ingram et al., 2010).

Recent years have shown that access to cheap food has led to an explosion of obesity-related problems in developed nations. In fact food prices and food affordability are still main causal factors of food choices, obesity and non-communicable diseases (Lee et al., 2013; Brunori and Guarino, 2010). Food consumption patterns vary with different lifestyles and are characterized by wide gaps in the frequency and in the amounts consumed (Johnston et al., 2014). The often-strong focus of consumers on low-price and convenience products overcome concerns for the risks of obesity or diabetes, generated by overconsumption of these foods (Ericksen et al., in Ingram et al 2010, p.132). Moreover, increases in calorific intake are also associated with shift in eating habits such as a greater intake of sugar and other calorific sweeteners, more frequent consumption of foods away from the home and in fast foods. In fact, the nutritional quality of meals prepared at home can be quite different to that of meals acquired outside (vending machines, restaurants and fast food outlets) (Nielsen and

Popkin, 2004). Furthermore, generally, out-of-home food consumption diminishes control over the amounts of calories within- and the nutritional quality of the foods consumed, especially calories provided by fats and sugars. In terms of energy balance, as well as the energy that enters the body, it is also important to consider the amount of energy expended by the consumer. Changes in food consumption patterns also imply the adoption of habits, or the abundance of jobs, leisure and transport options that are mainly sedentary (Swinburn et al., 1999). It also must be mentioned that policies and processes of globalization promote excessive consumption of calories (UNSCN, 2000; Garrett and Ruel, 2005; Friel and Lichacz, 2010).

Such dietary changes, characterized by consumption patterns that are increasingly homogenized and based on few global crop commodities and highly processed food products, generate also declines in diversity in human oral and gut microbiota, negatively impacting health and leading to obesity and overweight (Lozupone et al., 2012; Khoury, 2013).

Changing consumption patterns have been identified as a response to rising levels of obesity, cholesterol levels, and other diet-related illnesses (Burch and Lawrence, 2010). This is slowly leading to public awareness campaigns and community movements for more healthy diets (Barling et al, 2009; Obersteiner et al.,in Ingram et al., 2010). Cultural knowledge on preparing varied diets and on nutritional and health benefits of the foods can contrast the negative effects of changing consumption patterns (Termote et al., 2010; Kuhnlein et al., 2009).

As in ecological systems, increasing diversity in gut microbiota may confer further resilience through bacteria likely to have high functional response capacities, hence helping consumers to avoid the effects of a decreased dietary diversity (Lozupone et al., 2012). Therefore, dietary therapeutic strategies to improve gut microbiota, may represent appropriate treatments to counteract overweight and obesity and manage metabolic health (Cardoso et al., 2013; Nadal et al., 2009; Lopez-Legarrea et al., 2014).

Developing policy to warrant food security is a critical challenge that needs inclusive and integrated analytical approaches (Maxwell and Slater, 2003) and the involvement of the stakeholders is key to building up a framework and to assigning hierarchy to measurements (Aubin et al., 2013). Experimental research and case studies, however, are required to show if this approach (SES and Vulnerability/Resilience) is useful for food system management. There is also a need for outcome-orientated assessment criteria to focus on food security (Ericksen, 2008 ES). There is a call for system approaches to capture the dynamic processes between and within the food system activities, nutrition and health, and environmental outcomes. Computational complex systems modeling techniques aim at capturing the co-evolution of human and biological systems, and the complexity of human decision-making (Hammond RA and Dubé L, 2012). They allow exploring key processes and outcomes of the analyzed systems for food and nutrition security, delivering innovative and deeper insights at the environmental level. Efforts for strengthening the understanding of the theories of vulnerability and resiliencies within the food systems, through the social-ecological systems frameworks, are needed to explore the sustainability of the food system.

1.4 - Insights on a framework to explore the sustainability of the food systems

Research analyses of Food Systems and Food Security through the SESs 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 level by several international research teams and institutions from a global perspective. Four approaches - of different size and caliber - are reported here as examples.

Global Environmental Change and Food Systems-GECAFS

Global Environmental Change and Food Systems (GECAFS) was a ten years long (2001-2011) international and interdisciplinary research comprehensive programme aiming at understanding the linkages between food security and global environmental change. The objective of GECAFS was to identify strategies to cope with the impacts 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 socioeconomic and biogeophysical components. The project delivered an innovative conceptual and analytical framework and methodological tools, to investigate how global environmental change affects food security at regional scale, strengthening multidisciplinary efforts and engaging development communities in policy discussions to improve food security. The project focused 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 (GECAFS, 2014; Ingram et al., 2010)

2nd EU SCAR Foresight Exercise

In the 2nd Foresight Exercise (2008) of the Standing Committee for Agricultural Research (SCAR) of the European Union, it was considered insufficient to simply look just at the multiple dimensions of food security (availability, access and utilization). It was thus proposed to enlarge the analysis to the several biophysical and socioeconomic constraints that are determinants of a state of uncertainty of the food system. The foresight report attempts to answer the explicit question "how to reduce the vulnerability of social, economic and ecological systems", fostering for a systems perspective, 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 details and justified several sets of drivers of change (economic, social, environmental, technological, policy) at a global and European level. This effort is directed towards a wider resilience perspective beyond the narrow view of food security, changing attitudes to risk, and privileging diversification over specialization (SCAR, 2008).

TRANSMANGO

TRANSMANGO is an ongoing EU 4-year research project - under 7th Framework Programme - that aims at obtaining a comprehensive image of the impacts of the global drivers of change (climate, economic concentration and market structure, financial power, resource competition, marginalization, property rules, geo-political shifts, consumer preferences, consumption patterns and nutritional transition) on European and global food demand and on raw material production, and on food flows. The research focuses on the vulnerability and resilience of European food systems in a context of socio-economic, behavioral, technological, institutional and agro-ecological change and aims to improve 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 is conceived at different levels to pinpoint the directions for European policies that aim to tackle these multiple challenges. Through this scientific systemic approach and modeling, the involvement of a wide range of stakeholders, and the designing of scenarios for the desired transition pathways in the food system the project aims to understand the sustainability frontiers of different food production systems under the new unfolding conditions and the vulnerabilities of European food systems vis-à-vis future shocks and stresses, and how these may affect FNS focusing on the diversity of local situations within the EU and within regions (TRANSMANGO, 2014).

Metrics of Sustainable Diets and Food Systems

"Metrics of Sustainable Diets and Food Systems" is a multi-institutional small-scale project (Bioversity International and CIHEAM-IAMM, 2014) and its aims consisted of exploring the different approaches to assess the sustainability of diets and food systems, establishing a multidisciplinary taskforce of experts, and identifying a shortlist of indicators for sustainable diets and food system. The initial focus was in the Mediterranean region at a sub-regional level. 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. It was considered key to assess stocks of and changes in human and natural assets. 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 analyze the sustainability of critical food and nutrition security issues. A double set of drivers of change and food and nutrition security context specific issues were identified at a subregional level. This theoretical modeling exercise allowed the identification of a first suite of indicators. A reduced pool of metrics was then obtained through an expert-based elicitation process (Delphi Survey), moving beyond subjective evaluation and reaching consensus. This small-scale initiative is mainly oriented to a specific and technical selection of indicators.

The common thread that links these four different programs (for size and aims) is the approach that is built on the dynamic perspective of the social-ecological systems and the related 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. Because of the SES scientific approach, the geographical analysis of the food system is applied at regional level.

Contribution of the SESs frameworks and Vulnerability & Resilience theories to Sustainability analysis

Despite the strong orientation of the applications of SESs frameworks and vulnerability and resilience theories towards sustainable development interventions and exploring the biophysical factors that endanger the sustainability of social-ecological wellbeing, the conceptual connectivity and relationship with sustainability is still not obvious. Starting from Turner et al. (2003) there has been a strong effort in encouraging considering the usefulness of vulnerability and resilience research for sustainability science.

SESs frameworks for Sustainable Development

Various frameworks have been developed aiming at defining a common language, framing research and guiding to a sustainable development of SES (Gallopín et al. 2001, Holling and Allen 2002, Turner et al., 2003, Ostrom 2007), and the SESs frameworks variables have been key for identifying sustainable outcomes in natural resources management. The variables selected through the SESs frameworks explain the dynamics and the interactions in the social and ecological systems and the framework provides also further variables for exploring the potential sustainable development and management strategies of a social-ecological system (Binder et al 2013; Schluter et al., 2014). This type of framework is suitable for the analysis of complex social-ecological issues that implies dynamic interactions, and for answering

research questions about what are the characteristics, activities and dynamic factors of the system leading to, or impeding sustainable management (Binder et al 2013). Scoones et al. (2007) support a new science for sustainability that joins in established perspectives from natural sciences together with social science perspectives, and also a positivist and reductionist analytic together with more integrative, holistic, multidisciplinary and multi-stakeholders scientific approaches (Holling, 1998). Moreover, Schroeter et al. (2005) foster the link between the common goals of sustainability science and global change vulnerability assessment towards the suitability, efficacy, equity, and legitimacy of the outcomes for further sustainable interventions and development pathways (Kates et al., 2001; Clark and Dickson, 2003; Yu et al., 2012). Indeed, the concepts of resilience and adaptive capacity are often associated with sustainability (Conway, 1985; Strunz, 2012). Resilience, vulnerability and adaptability concepts have been applied in interdisciplinary research and broadly developed as proxies for sustainable strategies (Turner, 2010), through the hypothesis that a pretty resilient, slightly vulnerable and strongly adaptable system could maintain its functions over the time (Callo-Concha, 2014). 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).
Building on the shift of the understanding of sustainability from the formal definition of Sustainable Development (UN, 1987) - as threefold focus of the human efforts (Martins et al., 2007) - to a widely established perspective of sustainable systems that are dynamic in response to unattended events and disturbances (Holling, 2003), many approaches were identified to systemize the study of change. Thus sustainability can be described as the ability of a system to rebound from shocks and stresses (Holling, 1993; Ludwig et al., 1997; Folke et al., 2002; Scoones et al., 2007). This latter perspective is key to explore and anticipate the trends of the changing phenomena occurring, to reduce impact, and to foster towards the system pathways in the analysis of sustainability (Callo-Concha, 2014). Sustainability focuses on pressures affecting the perpetuation of life support systems, and provides practitioners and decision makers with understanding on these disturbances, their implications, and the ability of the system to cope with them (Turner, 2010). Specifically for identifying sustainable

solutions to world agrofood systems it is considered key to account and explore the dynamic uncertainty represented by a set of key drivers of change (Thompson et al., 2007).

Operationalizing Vulnerability & Resilience for a system analysis

Within the SES's analysis, the theories of vulnerability and resilience have proved to be a useful framework for understanding the dynamic interconnectedness between humans and the environment, and to offer models for improving society's capacities 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 key for implementing sustainable management strategies and actions (Rammel et al. 2007, Fulton et al. 2011; Cabell and Oelofse, 2012). Nevertheless there is still a need for further understanding of the dynamics of sustainability of SES (Carpenter et al. 2009; Schluter et al., 2014) and for a deeper comprehension in social and sustainability science in global change and food security for assessing the food system's vulnerability, and the socioeconomic and political strategies of adaptation (Yu et al., 2012).

However resilience and vulnerability are problematic to operationalize through precise assessment methods (Cumming et al., 2005), for their theoretical and multi-dimensional nature (Cabell and Oelofse, 2012). Scoones et al. (2007) underline that system functions have to be sustained, face to a set 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) proposes, 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 observing how different conditions of sustainability might have different consequences for the resilience of the system, with respect of its abilities to cope with change through the available socioeconomic, environmental and institutional assets.

In order to structure the vulnerability and resilience analysis of the social-ecological systems towards a more sustainable future, Cabell and Oelofse (2012) remind 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 sub-global, or sub-continental 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 resources 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 in all ways, before any vulnerability and resilience assessment is necessary to draw artificial boundaries to define a study area (Schroeter et al., 2005). Thus, considering that vulnerability is extremely context-specific (Cordell & Neset, 2014) and that global change is manifest through sub-global or regional driving forces, cross-scale trade-offs will need to be identified.
When applied to the food system, the system thinking gives us a dominant perspective that allows for global complexity and nonlinearity (Ulanowicz, 1997; Tower, 2012). A complex system refers to a system constituted by numerous components with numerous types of relationships, and presenting as a whole more characteristics than as a single component individually. Several approaches, analytical frameworks and fields of knowledge originate from these principles, such as systems dynamics, systems of systems, ecological thinking, ecosystem approach, systems thinking, etc. (Callo-Concha, 2014).

Assessing vulnerability to sustainability problems

Starting from the analytical approach of vulnerability and resilience in relationship 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 meet the challenge to assess vulnerability to sustainability problems (problems such as climate change, natural resources depletion, peak oil, market and political instability etc.): 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 the time for current and future vulnerabilities; study of solutions-oriented adaption and system resilience strategies; policy-relevance.

Several scholars 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 approach such as mathematical models (e.g. Fletcher et al., 2006) and also building more conceptual models of SES (Resilience Alliance, 2010). However it is proved 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, referring to the Carpenter et al.'s question (2001) "the resilience of what to what." (Cabell and Oelofse, 2012). To answer this question in two different works it is possible to find considerable efforts relevant to the need of a "rule of thumb" through defining a common methodological step-processes for the assessment of vulnerability and resilience from Schroeter 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 proved key in the investigations of complex social-ecological systems (Leach, 2008), there is still a need for appropriate metrics - in order to measure the conditions of the system and the stages that have been gained towards resilience - that could be met through developing more flexible process of identification of indicators and proxies (Cabell and Oelofse, 2012). Moreover, since there is a growing acknowledgment that the impact of food security research on decision making need to be strengthened, the approach of social-ecological systems science is considered as the key to support decision makers in accounting the broad sets of interplaying stressors towards definition of resilience solutions (Vermeulen et al., 2013; Vervoort et al., 2014). Hunger problems rely also on the increasing complexity of food systems and an analysis focusing on system's dynamics, interactions, feedbacks and non-linear relationship could contribute to identify resilience pathways (Ramalingam et al. 2008, Thomp-son and Scoones 2009; Gerber, 2014). However vulnerability and resilience theories are not normative concepts (Adger, 2006), and then need to be used and integrated conjointly with other normative concepts, in order to create a constructive dialogue with policy-makers (Leach, 2008; Plummer in Krasny et al., 2011).

Innovative and appropriate approaches to analysis and assessment should still focus on complexity of food system for their intrinsic entangled and questioned nature (Foran et al., 2014). For unraveling essential problems in the analysis of social-ecological systems, inter and transdisciplinary research is largely deemed as extremely helpful (Carpenter et al., 2009; Hammond & Duve', 2012; Ostrom, 2009; MA 2005, Liu et al. 2007, Huber et al., 2013), especially in terms of assessment of wide sets of potential outcomes, agreement within multiple stakeholders with different goals and intervention pathways, and modeling 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 (Engle et al., 2013; Ericksen et al., 2009; Janssen & Anderies, 2013; Saldarriaga et al., 2014).

Despite valuable and numerous efforts, most applications of the social-ecological systems frameworks still belong to the scientific community, whilst development practitioners' interest for this framework might inhibited for its system-orientation and problems with agency that may not be enough developed or studied (Foran et al., 2014). Frameworks, theories, and models are the elementary units that the scientific community applies for 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). However, such more integrative and holistic science - also within interdisciplinary context - might imply reductionist analytic approaches that can be refined through dialogue and interaction across disciplines, sectors, policy debates and coordination (Holling, 1998; Scoones, 2007).

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 studied systems and the integration and development of knowledge, theories, and approaches from different disciplines (Schluter et al., 2014). Attempts of integration of different frameworks for analyzing social and ecological systems have been proposed, for instance by Prosperi et al. (2014) who attempt to integrate the vulnerability framework into the application of the SES frameworks for the food system, and also alternatively by Loring and Gerlach (2013) who propose to integrate the Water-Food-Energy nexus into a diagnostic application of the SES frameworks.

1.5 - Conclusions

Food and nutrition security - as principal outcome of the food system - need to be sustained over time. A deeper understanding and knowledge about the interrelated dynamics of change - that govern the complexity of the food systems - are necessary to identify the threats of the sustainability of the food systems. Scholars and policy-makers call for metrics of food security and for sustainability of the food system, in order to provide decision-making with appropriate information (Barrett, 2010; Dicks et al., 2013).

Considering food systems as complex social-ecological systems - thus analyzing together natural and social systems and their interactions as one system with critical feedbacks throughout temporal and spatial tiers - interdisciplinary and integrated investigation approaches become key for exploring and designing effective responses to human-environment interactions related to food and agriculture in a unpredictably changing context (Ericksen, 2006; Thompson et al., 2007). Several studies identify vulnerability and resilience for helping draw causal dynamic interactions affecting the sustainability within the food systems. Building on a SES framework for the food system, vulnerability and resilience theories operationalize a causal pathway to identify which are the variables concerned towards the sustainability of the food system outcomes. A set of indicators of exposure, sensitivity and resilience could proxy the variables that describe the sustainability interrelations underneath the sustainability of the food systems and could be selected through an interdisciplinary and reproducible method. However, first it is necessary to shape a methodological organized structure, identify the driving forces to which the food system might be vulnerable, and categorize the food system unit that are likely to be exposed. In fact the primary goal of assessing resilience is to identify vulnerabilities in social-ecological systems to create a more sustainable future for people (Berkes et al., 2003; Cabell and Oelofse, 2012).

However, while vulnerability and resilience theories are helpful as metaphors, in metrics they are still considerably weak tools for assessment (Carpenter et al., 2001; Cabell and Oelofse, 2012). According to Cumming et al. (2005), resilience and vulnerability are problematic to operationalize for their abstract and multidimensional nature. Furthermore - since it is system-oriented - the social-ecological systems frameworks approach is still a research tool exclusive of the scientific community and not yet suitable for development practitioners because of limited options for agency (Foran et al, 2014). Also integration of different theories, models and frameworks originating from various disciplines might lead to analytical reductionism in the study of complex and interrelated food systems (Scoones, 2007). Further problems might derive from the multiple temporal scale and spatial level that need to be considered within a complex food system.

Taking into account these factors enlightens the challenges that the assessment of vulnerability and resilience implies - within the study of the sustainability of the food system - in order to satisfy the consideration of a set of aspects such as the coupled human-environment systems, complex interactions and driving forces, nested spatial scales, involvement of stakeholders through participatory process, dynamic assessment over time, providing information for decision- and policy-makings towards resilience.

In the context of social-ecological system and vulnerability/resilience analysis of the sustainability problems affecting contemporary food systems, these efforts should be directed towards the rising call for system approaches - to capture the dynamic processes between and within the food system activities, nutrition and health, and environmental outcomes (Allen et al., 2014) - and for developing metrics and measurement mechanisms for the sustainability of the food systems to give policymakers information and trade-offs data for intervention and dialogue with the stakeholders (Johnston et al., 2014).

Since at now there are no global common metrics to assess the sustainability of a food system (Vinceti et al., 2013), a consistent range of evidence-based sustainability metrics and standards should be identified to conduct analyses of the quantitative linkages between food security, nutrition, diets, health, agricultural productivity, resource use, environmental impacts, and costs and benefits (Beddington et al., 2012) through joint multidisciplinary efforts of professionals coming from nutrition, agronomy, public health, education, policy- and decision-making and food sector (Tilman & Clark, 2014).

Aims

This thesis builds on the social-ecological systems (SES) frameworks and the vulnerability and resilience theories for identifying an assessment tool that expresses the causal dynamics in the interactions (or interplays) between global change drivers and food security outcomes, to guide until the selection of appropriate metrics. In the introductory chapter a wide literature review was presented in order to describe the interest of the social-ecological system frameworks - for answering questions about the sustainability problems that affect the function of the food system - and the previous and future opportunities provided by a vulnerability and resilience analysis. The second chapter describes food systems as complex social–ecological systems, involving multiple interactions between human and natural components. A strong focus is on nutritional patterns and environment structure that are interconnected in a mutual dynamic of changes. The systemic nature of these interactions calls for multidimensional approaches and integrated assessment and simulation tools to guide change. In this chapter conceptual modeling frameworks are described articulating the synergies and tradeoffs between dietary diversity and agricultural biodiversity, and associated ecosystem functions that are crucial resilience factors to climate and global changes. In the third chapter we identify the fundamental sustainability properties of the social-ecological framework, describing how the vulnerability and resilience theories contribute to the understanding of the causal dynamic interactions of the socioeconomic and biophysical factors acting in the food system. Elements found in literature are reported for illustrating how the vulnerability and resilience approaches are applied for shaping causal interactions building on potential impact and recovery potential. In the forth chapter we illustrate the formalization of the food system as a dynamic system. The dynamic variables of the food system are identified through the mathematical modeling exercise of the conceptual elements described above, and through the first steps of a vulnerability/resilience assessment methodology allowing define the study area, develop context-specific knowledge of the social-ecological system (identifying specific drivers of change), hypothesize stresses and interactions with the vulnerable issues of the food systems, and finally formalize these interactions into eight causal models (of vulnerability/resilience). Then we discuss this modeling approach within the context of the assessment of sustainable food systems. In the conclusions we draw further perspectives of research for identifying specific indicators through a vulnerability/resilience modeling exercise. The last chapter of the thesis illustrates the process of selection of metrics through an expert elicitation method (Delphi survey) that guided to the identification of a reduced pool of indicators through a shared consensus.

The general aim of this thesis is to analyze and explore the sustainability of the food system through identifying a systemic set of metrics at the Mediterranean level. This general aim involved three specific goals:

Developing a multidimensional framework to improve the dynamic understanding of the sustainability of food systems and diets, applicable to countries of the Mediterranean region.

Identifying the main variables to formalize and operationalize the abstract and multidimensional concepts of sustainable food systems.
Defining metrics for assessing the sustainability of food systems and diets, at a subregional level, combining a vulnerability and resilience framework and a Delphi elicitation process.

Preface to Chapter 2

The stark observation of the co-existence of undernourishment, nutrient deficiencies and overweight and obesity, the triple burden of malnutrition, is inviting us to reconsider health and nutrition as the primary goal and final endpoint of food systems. Agriculture and the food industry have made remarkable advances in the past decades. However, their development has not entirely fulfilled health and nutritional needs, and moreover, they have generated substantial collateral losses in agricultural biodiversity. Simultaneously, several regions are experiencing unprecedented weather events caused by climate change and habitat depletion, in turn putting at risk global food and nutrition security. This coincidence of food crises with increasing environmental degradation suggests an urgent need for novel analyses and new paradigms. The sustainable diets concept proposes a research and policy agenda that strives towards a sustainable use of human and natural resources for food and nutrition security, highlighting the preeminent role of consumers in defining sustainable options and the importance of biodiversity in nutrition. Food systems act as complex social–ecological systems, involving multiple interactions between human and natural components. Nutritional patterns and environment structure are interconnected in a mutual dynamic of changes. The systemic nature of these interactions calls for multidimensional approaches and integrated assessment and simulation tools to guide change. This chapter proposes a review and conceptual modelling framework that articulate the synergies and tradeoffs between dietary diversity, widely recognized as key for healthy diets, and agricultural biodiversity and associated ecosystem functions, crucial resilience factors to climate and global changes.

Chapter 2

Agricultural biodiversity, social–ecological systems and sustainable diets: Towards resilience for food security[1]

[1] *This chapter is adapted from:*
Allen, T., Prosperi, P., Cogill, B., & Flichman, G. (2014). Agricultural biodiversity, social–ecological systems and sustainable diets. *Proceedings of the Nutrition Society*, 73(04), 498-508.

2.1 - Introduction

Humanity faces a global nutrition crisis, with the dual problem of hunger and obesity. A total of 842 million people still suffer from undernourishment (FAO, 2013) while obesity has become a significant public health issue with 500 million obese adults (Finucane et al., 2011). More than 1 billion adults are projected to be obese by 2030 if no major effort is made (Kelly et al., 2008). Meanwhile, climate change and environmental degradation are massive threats to human development. Indisputable and unprecedented changes in extreme weather and climate events have been observed and will increasingly have detrimental impacts on livelihoods, particularly in combination with other environmental threats (IPCC, 2013). Above all, global biodiversity is constantly declining, with substantial ongoing losses of populations, species and habitats.

Vertebrate populations have declined by 30% on average since 1970, and up to two-thirds of species in some taxa are now threatened with extinction (UNEP, 2012). These global changes have major implications for food and nutrition security.

There is a bi-directional relationship between the environment and food. Human subjects depend on the goods and services provided by natural and managed ecosystems to meet their food needs. The production of food and its nutrient content are inextricably linked to the environment. Ecological interdependences are key factors for the dietary content of most living species we consume (Frison et al., 2011). The observed environmental degradation and biodiversity depletion, in particular, are affecting the food systems, with implications for yield, quality and

Affordability (MA, 2005). At the same time, processes along the food chain, from agricultural production to food consumption, produce other outputs than food that are returned to the natural environment, such as pollution or waste. Human activities impact the diversity of organisms

found in ecosystems, and thus influence the provision of ecosystem services.

The links between environmental degradation and food system activities are increasingly recognised and translate into joint negative environmental and nutritional outcomes (Ericksen et al., 2009; Gregory et al., 2005). The sustainable diets' research and policy agenda essentially aim at putting nutrition and health at the core of sustainable development. However, there is not a clear understanding of the interactions between food systems; their production activities and subsequent outputs, ecological processes and human nutrition. This has resulted in a perceived lack of evidence of the benefits of agrobiodiversity on nutritional outcomes from food systems, preventing agrobiodiversity from being a key consideration in food and nutrition policies.

Since the processes underlying nutrition insecurity and diet-related environmental, economic and social unsustainability derive from a shared food system, a recurrent fundamental question is: what types of system shift could create an enabling environment for sustainable diets? Research has a critical role in answering this type of question. System dynamics are widely considered of particular interest to food and nutrition security (Hammond and Dube, 2012). Starting from a conception of food systems as social–ecological systems, thus fully tackling the systemic dimension of the food sustainability question, this chapter proposes a review and a conceptual modeling framework that articulates biophysical processes with socio-economic dynamics. Within this coupled human–environment framework, taking into account the determinants that influence food consumer behaviours will be key to improving strategies that mitigate negative patterns on health and the environment. It will help frame the agricultural biodiversity's role in nutrition and develop modelling tools for the policy-makers to guide changes towards sustainable diets and food systems.

2.2 - Sustainable diets: a new concept calling for changes

A nutrition-driven perspective

Gussow and Clancy (1986) were the first to suggest the term 'sustainable diet' to describe a diet 'composed of foods chosen for their contribution not only to health but also to the sustainability (the capability of maintenance into the foreseeable future) of the (. . .) agricultural system' (Herrin and Gussow, 1989). Literally, the concept of diet in nutrition refers to the sum of foods consumed by a person.

Whole diet, or dietary pattern, analysis has emerged as an alternative and complementary approach to the study of individual nutrients or foods, highlighting the dynamic and multiple factors involved in eating practices (HU, 2002). It helped better communicate healthy eating messages that emphasise a balance of food and beverages within energy needs (Freeland-Graves and Nitzke, 2013). More fundamentally, adopting a whole-diet approach is now seen as necessary to examine the relationships between nutrition and health (Popkin, 1997). It reflects the increasing recognition of the multidimensional nature of diets and diet-related diseases, from nutrient intakes and metabolism to food consumption behaviours and attitudes (Kant et al., 2009).

Multidimensionality is further enhanced as the impacts of diets not only on health, but also on the environment or the economy, are considered to assess the sustainability of food choices. Participants at the 2010 International Conference jointly organised by the Food and Agriculture Organization and Bioversity International agreed on a common definition of sustainable diets as 'those diets with low environmental impacts which contribute to food and nutrition security and to healthy life for present and future generations.

Sustainable diets are protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable; nutritionally adequate, safe and healthy; while optimising natural and human resources' (FAO/Bioversity, 2012).

The sustainable diet concept advocates for a more consumer-driven thinking on the sustainability of agriculture, promoting a research and policy agenda that introduce nutrition as one of its core dimensions. It claims that understanding the determinants of consumer choices can improve agricultural and food systems, the environment and the health. More fundamentally, it emphasizes the health and food security purpose of food systems, and highlights the need for quality, not just quantity or access. Advocates promote economically, socially and environmentally sustainable food systems that concurrently ensure 'physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life' (UN, 1996). This reminds us that food, or more precisely feeding people, is agriculture and food systems' main reason for being (Haddad, 2013). As such, the concept of sustainable diets provides a food and nutrition security-orientated perspective on the question of the sustainability of food systems.

Food security and sustainable development

Food and nutrition security is a major concern today with still 842 million people undernourished (FAO, 2013). Resulting undernutrition is affecting millions of people, in particular children under 5 years with about 165 million stunted children in developing countries (UNICEF, 2013).

Sub-Saharan Africa and South Asia, with wide subregional variation, are the most affected regions by stunting. Undernutrition is accompanied by, in some cases linked to, micronutrient malnutrition. Malnutrition involves privation in essential micronutrients with low food diversity. Deficiencies in essential micronutrients have detrimental effects on health; vitamin A is required for multiple physiological processes, ranging from vision to embryonic development; iron is an important component of haemoglobin, the oxygencarrying component of blood; iron also plays an important role in brain development and iron-deficiency anaemia can impair the cognitive development of children; iodine is essential for healthy thyroid function and growth, etc. Simultaneously, increased prevalences of overweight and obesity are reported in both low- and high-income countries and represent the major health threats. Excessive fat accumulation, measured by the BMI, is acknowledged to be a risk factor for various non communicable diseases and health problems, including CVD, diabetes, cancers and osteoarthritis (WHO, 2014).

Simultaneously, climate change and environmental degradation are major challenges to sustainable development.

The global climate and other life-supporting environmental systems are seriously perturbed and depleted (IPCC, 2013). These changes include higher temperatures, drought-prone and long-term drying conditions in some

sub-tropical regions, rising sea levels, acidification of oceans, declining water quality, depleting fish stocks, increasing frequency and severity of floods and other climate-related natural disasters. Biodiversity is also at risk, with 20930 species and ecological communities known to be threatened (IUCN, 2013). Biodiversity, the basis of ecosystem health and future food security, has been more seriously harmed by human activities in the past 50 years than at any other time in human history (UNEP, 2012).

Agriculture and the food sector have historically been major contributors to environmental degradation. For instance, irrigated agriculture globally accounts for 70% of the consumption of freshwater resources (OECD, 2013).

However, there is a bi-directional relationship between environmental

degradation and food system activities. People, particularly those living in developing countries, are vulnerable to environmental changes that result in reduced quantity, quality and affordability of food.

Similarly, nutrition transition and food system transformation go together. The current global health crisis of malnutrition, both in developed and developing countries, and the contemporaneous urging environmental degradation present new challenges for food systems and calls for changes. Improved food systems could be a major partner in the environmental solution.

Diets as system outputs

A crucial question is then: can optimal diets be derived that concurrently meet dietary requirements while reducing detrimental environmental impacts? Contrary to conventional wisdom, recent evidence suggests that high nutritional quality products might not be necessarily more environment-friendly. Although plant-based foods have lower greenhouse gas emissions (GHGE) per unit weight, better quality diets were found associated with significantly higher GHGE after adjustment for energy intake (Vieux et al., 2012; Vieux et al., 2013). So, can consumers lower, for example, their carbon footprint through making changes in the kind of food they buy, and still meet nutritional adequacy recommendations? MacDiarmid et al. (MacDiarmid et al., 2012) derived what would look like such an optimal diet for a representative UK consumer for different GHGE reduction targets.

Using mathematical linear programming, they conclude that such a diet can be achieved for the GHGE objectives set for 2020 (−25 %); however, meeting the targets for 2050 (−70 %) and dietary recommendations will require a 'radical shift in food consumed'.

Ad hoc constraints were added to the model to maintain simulated diets within consumers' acceptability limits.

These results clearly show that demand-side approaches to the problem of environmental unsustainability are desirable and likely to contribute to improvements. However, as highlighted by MacDiarmid et al. (2012), GHGE reductions should be made to both the demand and supply sides within the food chain, in particular to attain longer-term objectives. If other environmental, economic, social and ethical aspects of sustainability were to be included in the optimisation model, while strengthening the acceptability constraints, one can wonder if feasible solutions can be derived by changes at the sole food basket level. Linear optimisation theory tells us that if there are x decision variables, then a set of x equality constraints needs to be specified for one unique optimal solution and vice versa. Any extra equality constraints will overspecify the problem. If feasible solutions are to be identified, extra decision variables need to be considered. In other words, other levers need to be operated jointly with actions encouraging behaviour changes.

The processes underlying food insecurity and diet-related environmental, economic and social unsustainability derive from a shared food system. For instance, GHGE are not food attributes, but outputs of different activities along the value chain. Food consumption is a heavy contributor to 'embodied' or indirect emissions in products that result from activities prior to purchase (Kim and Neff, 2009).

In practice, these indirect emissions are very hard to be accurately estimated and attributed to a good or an individual.

Modelling exercises of optimal diets have had to use so far averages coming from life-cycle assessment studies on, sometimes, rather aggregated food groups. There might thus be a high degree of variation around these average estimates. For instance, Lindenthal et al. (2010) report substantial differences in terms of GHGE between organic production methods as compared with conventional farming in Austria (10–21% lower CO2-eq/kg product for organic dairy, 25% for organic wheat bread and 10–35% for organic vegetable.). Similar studies elsewhere have reported the same results (Kustermann et al., 2008; Petersen et al., 2006).

Consumers stand at the top of the food system and diets are outputs of longer and more complex food chains encompassing several activities. Technologies and policies affect the overall environmental performances, food security and health outcomes (Ingram, 2011). To derive optimal sustainable diets, we need to look at all the variables that influence the flow of activities along the food system.

These are the levers to act upon. To assess and enhance food sustainability, focus needs to move beyond the food basket while ultimately bearing in mind that diets and nutrition are the final reason for being of the food system. Burchi et al. (Burchi et al., 2011) define a system as 'a set of elements that function together as collective units which have properties greater than the sum of their component parts'. The food system concept describes the required inputs, processes and generated outputs involved in the provision of food and nutrients for sustenance and health, including growing, harvesting, processing, packaging, transporting, marketing, consuming and disposing of food (Ericksen et al., 2009; Ratoin and Ghersi, 2010; Rutten et al., 2011).

The current joint crisis of malnutrition and unsustainability has roots in agricultural and food systems that do not deliver enough essential nutrients to meet dietary requirements for all (Graham et al., 2007; DeClerck et al., 2011). The solution to sustainable diets lies both in sustainability-orientated food choices and in changes in the food systems. And modern societies depend on complex social–ecological systems to provide food (Ericksen et al., 2009; Fraser et al., 2005; Turner et al., 2003; Ostrom, 2009).

2.3 - A complex human–environment system

Food and nutrition as ecosystem services

Agriculture and the food sector at large have a first-hand touchpoint with nature: crops need soil, water, insects for pollination, etc. The analysis of the relationships between resource acquisition and living organisms, at the heart of the sustainable diet concept in the case of human organisms, is also an ecological question, and can surely benefit from insights from ecology. Ecosystems consist of a community of species, or biodiversity, interacting with each other and with their environment. The product of these interactions, which include competition, predation, reproduction and cooperation, is essential to human wellbeing. Human subjects depend on goods provided by natural and managed ecosystems. These goods and other benefits provided by ecosystems to mankind are collectively referred to as ecosystem services (Ecosystem services were defined in the Millennium Ecosystem Assessment (2005) as 'the benefits people obtain
from ecosystems', both natural and managed. These services may be categorised as provisional (fibre, food, water and fuel), regulative (climate and disease regulation, water purification), cultural (aesthetics, heritage, education, recreation and spiritual) or supporting
services (nutrient cycling, primary production and soil formation)). All are processes through which ecosystem sustain human livelihoods. Food production is an ecosystem service central to human welfare (Costanza et al., 1997). The capacity of ecosystems to provide us with the energy and nutrition for our daily life fully depends on the foods that agriculture and food systems provide us. Clear from this process-based interpretation, human nutrition should be considered one of the most fundamental ecosystem services, or alternatively as dependent on several ecosystem services,

including provisioning, regulating, supporting and cultural services (DeClerck et al., 2006).

Agricultural biodiversity, or agrobiodiversity, is the sub-component of biodiversity that refers to the biological variety and variability of living organisms that are involved in food and agriculture. It can be considered at three main levels: ecosystem diversity, species diversity and genetic diversity (Heywood et al., 2013; UN, 1992). It includes habitats and species outside of farming systems that benefit agriculture and enhance ecosystem functions such as pollination, soil dynamics and control of GHGE. Agrobiodiversity comprises the constituents of biological diversity important to food and agriculture as well as for the agroecosystem (Frison et al., 2011; Brussaard et al., 2010). Furthermore, it is the result of the deliberate interaction between human subjects and natural ecosystems. Subsequent agroecosystems are thus the product of not just physical elements of the environment and biological resources, but vary according to cultural and management systems (Heywood et al., 2013). Agrobiodiversity includes a series of social, cultural and ethical variables.

Reduction in agrobiodiversity and simplification of diets

Modern agriculture and food systems are contributing to the simplification of the structure of the environment, replacing nature's biodiversity with a small number of domesticated plant species and animal breeds (Altieri, 2000). This process has been one of the main factors that allowed much of the human population to enjoy unprecedented levels of development and improved health. However, as efforts have been directed at maximising production and productivity, uniformity has replaced diversity within cultivated systems (Sage, 2013). Agricultural intensification, which implies specialisation and genetic standardisation, reduction of utilised species, conversion of forests and wild land to anthropogenic habitats, homogenisation of soils through amendments, is certainly the first humanrelated cause of biodiversity loss (Frison et al., 2011; Rosen, 2000; Tilman et al., 2002). The increase in food supply has thus come with important trade-offs that include soil degradation and loss of many regulatory and supporting ecosystem services. These trade-offs can impair the ability of the ecosystems to deliver the essential nutrients for human diets (Palm et al., 2007).

This increased reliance on domesticated species and selected crop varieties can be linked to a significant reduction in dietary diversity. Modern agriculture is genetically dependent on a handful of varieties for its major crops (Kahane et al., 2013). The world's agricultural landscapes are planted mostly with some twelve species of grain crops, twenty three vegetable crop species and about thirty-five fruit and nut crop species (Fowler and Mooney, 1990) (as a comparison, one single hectare of tropical rain forest contains on average over 100 species of trees (Perry, 1994); cited in (Altieri, 1999). This process of simplification of agriculture generated a model where only a small number of crop species dominate our energy and nutritional intakes. Three crops alone (rice, wheat and maize) account for more than 55% of human energy intake (Stamp et al., 2012).

Although varying in nutrient content, no single crop species is capable of providing all essential nutrients. Nutritional diversity is now widely recognised to be a key factor for adequate diets likely to satisfy the complex human nutritional needs (Arimond et al., 2010; Roche et al., 2008; Randall et al., 1985; Torheim et al., 2004). Evidence of the valuable
outcomes of diversity in decreasing malnutrition, morbidity and mortality (Frison et al., 2011; Tucker, 2001) is completed by indications of positive correlation with child growth and survival (Arimond and Ruel, 2004; Pelletier and Frongillo, 2003).

The importance of nutrient diversity for human wellbeing calls for dietary diversification. However, the quality of nutritional supply and human health is in danger because of a loss in biodiversity. A reduction in the consumption of varied, 'nutritionally-rich' and 'functionally-healthy' plant-based foods is reported in most developed and emerging countries (Johns and Eyzaguirre, 2006). The preeminent simplification of human diets, associated with changing lifestyles, led to nutrient deficiencies and excess energy consumption. However, the elimination of most essential nutrient deficiencies (most important micronutrients usually reported are vitamin A, iodine and iron, zinc; Graham et al. (2007) provide a list of fifty-one essential nutrients for sustaining human life) requires only small increases in the variety of food items an individual consumes (Ruel, 2003). As a result, balanced nutrition in human diet can depend significantly on the diversity within crops (Mouillet et al., 2010).

Ecological interdependences are key factors of the dietary content of most living species. Some lesser-known cultivars and wild varieties have been reported to be micronutrient superior over other more extensively utilised cultivars. For example,

recent analyses have shown that provitamin-A carotenoid content of bananas differs by a factor of 8500 between different cultivars (Burlingame et al., 2009).
In Micronesia, the local 'karat' banana has been found to contain high levels of provitamin-A carotenoids, which contribute to protection against vitamin A deficiency and chronic diseases, including certain cancers, heart disease and diabetes (Engelberger et al., 2003) (cited in (Sajise, 2005)). In this regard, the term 'neglected and underutilised species' or 'development opportunity crop' refers to those species whose potential to improve people's livelihood is not being fully exploited (given the current lack of detailed and comprehensive nutritional information about diversity within crops at the cultivar level and the role it plays in nutrition, the Food and Agriculture Organization has launched the INFOODS initiative (Mouillet et al., 2010; Padulosi et al., 2011). For instance, a local fruit, Berchemia discolor, was found to contribute in a low-cost manner to closing nutrient gaps in Kenya (Termote et al., 2013). Peach palm (Bactris gasipaes) provides, under low soil fertility and extreme rainfall conditions, starchy fruits with high protein density, rich in monounsaturated oleic acids, carotenoids, vitamin E and potassium (Graefe et al., 2013). Amaranth, as a leafy vegetable, is nutritionally comparable with spinach while showing strong photosynthetic activity and water use efficiency (Wang and Ebert, 2012; Ebert, 2014). The drumstick tree (Moringa oleifera) combines the traits of high yield and high nutrient density in essential micronutrients, vitamins, antioxidants and bioavailable iron, making it a good supplement for children and pregnant and lactating women (Ebert, 2014). All these examples demonstrate how intraspecific biodiversity and the consumption of neglected species and varieties can be essential to nutrition security.
Increasing the number of crops available to local communities, in particular in developing countries, increases the likelihood of obtaining the nutrients needed for healthy and productive lives (DeClerck et al., 2011). Deckelbaum et al. (2006) showed that biodiversity and hunger hotspots geographically correspond, reminding us of the link that Jared Diamond unravelled about the spatial relationship between biodiversity availability and society development (Diamond, 1997). This evidence, demonstrating the correlation between hunger and biodiversity-losing areas, confirms the need for local biodiverse agricultural systems.
DeClerck et al. (2011) further observed that improving functional agrobiodiversity in Kenya reduces anaemia incidence, and that interventions supporting environmental sustainability, through biodiversity, can have multiple direct and indirect outcomes on

human health and nutritional wellbeing. Similarly, in rice-based aquatic production systems, Halwart (2006) found that vegetal agrobiodiversity allowed improved biological diversity and diverse nutritional sources for human subjects (calcium, iron, zinc, vitamin A, some fatty acids and limiting amino acids). Moreover, through fish biodiversity, rice yields increase and the presence of several aquatic organisms in rice ecosystems allows a better biological control of vectors and pests. Animal and vegetal agrobiodiversity in rice-based ecosystems increases income through yield growth and lower costs for pesticides through biological control (Diamond, 1997). These issues suggest, for tackling malnutrition, but also other aspects of food insecurity, the need to link ecology and agriculture to human nutrition and health.

Agrobiodiversity and resilience for food security

On top of nutritional issues, agricultural biodiversity is an essential component in the sustainable delivery of a more secure food supply. Agrobiodiversity is the outcome of thousands of years of efforts by farmers, selecting, breeding and developing appropriate production systems and methods. It plays a crucial role in productivity and livelihood of farmers, by providing the wide range of resources they need to increase productivity in favourable settings or to adapt to variable conditions. Biodiversity simplification resulted in an artificial ecosystem that requires constant human intervention, whereas plant biodiversity allows internal regulation of essential functions in natural ecosystems (Altieri, 1999). Several nature- and human-related drivers of change threaten the ability of social–ecological systems to maintain vital functions and processes: climate change, natural resources exploitation, habitat depletion, pollution, etc.

Understanding how agrobiodiversity is likely to impact agricultural and ecosystems is key. Climate change is a potent risk to the world's food supply in coming decades, likely to undermine production and driving up prices (Godfray et al., 2010; Ingram et al., 2010). Agricultural biodiversity will be absolutely essential to cope with the predicted impacts of climate change. Crop genetic diversity provides partial resistance to diseases, and enables farmers to exploit different soil types and microclimates for a variety of nutritional and other uses (Altieri, 1999). Improved resilience, to climatic shocks among others, is observed in highly biodiverse ecosystems (Swift et al., 2004; Rees et al., 2001). In Malawi, Mozambique and Zambia, between 26 and 50% of rural households relied on indigenous fruits as a coping strategy during critical seasonal\

hunger periods (Akinnifesi et al., 2004; Powell et al., 2013). Furthermore, biodiversity in agroecosystems accomplishes multiple ecological services beyond the production of food such as: nutrients recycling, hydrological regulation, purification of toxic chemical compounds, etc. For instance, improvement in agroforestry biodiversity reduces nutrient leaching and soil erosion and refurbishes key nutrients from the lower soil layers (FAO, 2011). To assess the role of agricultural biodiversity in sustainable and secure food production, cross-sectoral approaches are necessary as potential benefits can be manifested at different ecological and human scales (Frison, 2011). Farmers also conserve, and modify their use of, agrobiodiversity to better adapt to different environmental conditions, but also to changing market conditions (Pascual et al., 2011). In Indonesia, the conservation of high levels of biodiversity in rubber agro-forests helped secure population livelihood during the 2008 fall of rubber prices by providing an alternative source of income from secondary products (Powell et al., 2013; Feintrenie and Levang, 2009). Agrobiodiversity can thus be seen as a crucial asset to keep multiple options open. As a general rule, increasing the number of species in a community will enhance the number of functions provided by that community, and will reinforce the stability of the provision of those functions (DeClerck et al., 2011).

2.4 Bio-economic modelling for biodiversity and nutrition

Modelling activities, capturing diversities

In recent years, there has been a significant development of bio-economic models, enhanced by the recognition of the multifunctionality of agriculture and the multiplicity of objectives assigned to the agricultural policies (Janssen and van Ittersum, 2007). The subsequent increasing demand for integrated assessment called also for more dialogue and co-operation between scientists from various disciplines, and bio-economic models have been advocated as an adequate tool for such a purpose (Kragt, 2012). Bio-economic models refer to models that couple both an economic and a biophysical component.

Brown (2000) more precisely identifies models primarily concerned with 'biological process (. . .) to which an economic analysis component has been added'.

Another kind of model consists of 'economic optimisation models which include various biophysical components as activities among the various choices for optimization'. In between, he suggests a third category that integrates in an interactive manner the biophysical and the economic modules. This last category genuinely deserves to be called 'bio-economic'.

At the heart of most bio-economic models lies the paradigm that, for analysing the relationships and tradeoffs between socio-economic systems and biophysical and ecological processes, and to help evaluate how management actions affect different policy objectives, it is necessary to model activities (Flichman et al., 2011). What produces biodiversity depletion or soil erosion is not wheat or maize production per se, but the way it is produced. And there are several ways of producing the same product.

The degree of pressure on the environment will depend on the crop selected and its combination with other crops, the tillage technique, the type of soil, the production system, the period of harvest, the seasonality and many other technical issues. It is therefore not adequate to associate a final product with a single simple production function. The relationships between a final product and the inputs associated with its production, highly non-linear because of the large set of possible combinations, might be better captured by considering the variety of activities or production processes.

Land, water, seeds (of different species and varieties), labour, energy, machinery, fertilizer, etc. are taken into account as inputs to the agricultural production. Food are outputs, as well as pollution, changes in landscape, depletion of natural resources, soil erosion, loss of underground water, habitat destruction, biodiversity losses, etc. There are numerous possible combinations of inputs to produce several outputs. Using an example from agricultural production, wheat systems do not only produce grain, but also straw and different types of pollution.

They are 'joint products' (Baumgartner et al., 2001; Pasinetti, 1980). Thus each activity can produce several products (e.g. grain, straw and pollution), and in turn each product can be produced by several activities (e.g. several ways of producing grain). As a consequence, modelling the relationships between a final product and the 'externalities' become even more challenging to synthesize.

Bio-economic models represent production activities in an explicit manner. A production activity describes a specific production process. Usually called an

engineering production function, it describes explicitly the relationships between factors of production and products
expressed in physical quantities (e.g., kg fertilizer/ha, m3 water for irrigation, etc.). In agriculture, an activity is defined by the technical coefficients that represent the use of inputs needed to produce different outputs (Flichman et al., 2011).
These engineering production functions, which use primal variables (physical quantities), constitute the essential link between the biophysical and economic processes. Models based on cost functions, which use dual variables (prices), can hardly analyse the relationships
between inputs and outputs in a straightforward and proper manner. The fact that one product is obtained through several production activities, explains in part the complex and non-linear relationships between inputs and outputs observed per product, which are difficult to capture mathematically. On the contrary, the average cost can more realistically be assumed equal to the marginal cost when considered per activity. Relationships between inputs and joint products by activity are thus linear functions of Leontief type. The use of engineering production functions creates a strong information demand, requiring data framed in terms of physical input–output matrices. However, thanks to this representation, positive and negative jointness can be simultaneously taken into account. This more direct approach can help assess the joint interactions between biodiversity and nutrition.

Biodiversity in bio-economic modelling

There are basically four approaches to introduce biodiversity or agrobiodiversity in bio-economic optimization models. In a normative approach, it is possible to include biodiversity conservation targets directly in a multiobjective function. Multi-objective optimisation models are goal-oriented models, where optimal decisions need to be taken in the presence of trade-offs between two or more conflicting objectives. Holzkämper and Seppelt (2007) developed a spatially explicit optimisation model with respect to ecological and economic goals, namely habitat suitability for three target species and profit losses from different land-use options. Results show that optimum agricultural land-use patterns differ between species, as well as between study sites. Groot et al. (2007) explore the synergies and trade-offs between financial returns, landscape quality, nature conservation and environmental quality in a spatially explicit land-use allocation model, which combines agronomic, economic and environmental indicators with biodiversity and landscape quality indicators. More specifically, their Landscape IMAGES model couples an agroecological model to amulti-objective optimisation algorithm that generates a set of alternative landscape configurations. An agroecological engineering approach was used to design production activities.

Alternatively, impacts on biodiversity of different land-use management options and policy scenario can be assessed through optimisation models. Schönhart et al. (2011) address the effects of land use intensity and landscape development on biodiversity at farm and landscape levels. Their integrated land use model combines a crop rotation model with a biophysical process model (erosion–productivity impact calculator) and a spatially explicit farm optimisation model. Field- and farm-specific crop yields, crop rotations and environmental outcomes of the biophysical model are inputs to the farm optimization model, which maximises total farm gross margin subject to resource endowments and several balance equations.

Decisions in integrated land use model are assumed to reflect actual producers' choices postulating efficient farm resource utilisation. This structure allows introducing landscape metrics, such as the Shannon's diversity index, to quantify the spatial biodiversity impacts of landscape development scenarios. Scenario analysis is used to assess the cost-effectiveness of different agro-environmental measures to achieve biodiversity targets. One asset of the integrated land use models is the inclusion of spatial modeling of landscape elements. Similarly, Mouysset et al. (2011) adopt a multi-criteria approach to assess jointly the impacts of public policy options on conservation of biodiversity and farming production. Assuming income maximizing farmers under technical constraints, the authors test different taxation scenarios on economic performances and farmland bird abundance.

As argued by Schönhart et al. (2011), biodiversity conservation targets can also be introduced in the model as constraints. Van Wenum et al. (2004) study optimal wildlife management on crop farms using integer programming.

They compute a wildlife-cost frontier at the farm level evaluating the optimal trade-off between species richness and total gross margins. Their model derives sets of management activities that maximise farm income under incrementally varying wildlife conservation requirements.

Results provide the extent to which stepwise increases in species richness objectives impact negatively farm profits.

A last approach consists of integrating agrobiodiversity at the core of the model in the definition of the agricultural activities. All the earlier examples of models that consider impacts on biodiversity are based, at least partially, on engineering production functions. It implies defining activities such as obtaining constant marginal costs. Combinations of crops and rotation schemes, in interaction with the environment and agronomic technique, on the farm at the field level have to be considered to specify activities. For example, maize, beans and squash (the indigenous 'American three-sisters') planted simultaneously would be modelled as a specific activity, different from an activity involving only one of the three crops or any other combination. The planting techniques used, either just in the same field or in the same hole, would also be distinguished. Conceptually, this approach by activity would allow setting agrobiodiversity at the core of the model, and better match an understanding of the environmental and nutritional outcomes of diets as system outputs. Indeed, specific environment and nutrition impacts can thus be specified by activity and not by product. However, one strong limitation regards data requirements. Given the wide array of possible combinations, a large number of technical coefficients, which enter the model as external variables, need to be available and properly estimated to result in real improvement to existing modelling exercise.

Joint assessment of nutrition and biodiversity

The increasing demand for integrated assessment, including nutrition (Hammond and Dube, 2012; Frongillo et al., 2013; Misselhorn et al., 2012; Remans and Smukler, 2013) calls also for bio-economic models integrating consumer choices and dietary patterns, and subsequent sets of food consumption and nutrition indicators. A nutrition-driven food system, which also ensures that environmental integrity, economic self reliance and social well-being are maintained and enhanced, places people, as consumers, as one of its central focus (Burchi et al., 2011). Not only should we be able to determine food and nutrient availability at the farm or food system level, resulting from the use of biodiversity for instance, but we also need to understand and consider how it translates into actual consumption at the household and individual level. To achieve this, models of food consumption patterns and behaviours need to be integrated into the bio-economic models. This type of tool will allow a proper nutritional analysis and evaluation of required changes in the food systems to reach sustainable diets. In the context of developing countries, farm household models offer the conceptual background to expand existing bio-economic farm models, to capture the interactions between ecological dimensions and agronomic decisions with consumers' choices (and acceptability of simulated options in terms of consumers' preferences) and nutritional outcomes. Small-holder farmers are vital for developing countries' economies, supporting today one-third of humanity (IFAD, 2014). Farm households, while increasingly selling and relying on markets, represent an 'easier to control for' food system at the smallest scale.

In the case of small-holder farmers in developing countries, the deciding entity is both a producer and a consumer. In the existence of market failures, non-separability regarding production and consumption decisions has to be assumed, and a farm-household approach becomes necessary (Sadoulet and De Janvry, 1995). Several attempts have been made to couple bio-economic and farm-household models (Janssen and van Ittersum, 2007; Holden et al., 2003; Kruseman and Bade, 1998; Ruben and van Rujven, 2001; Shiferaw et al., 2001). In particular, the Joint Research Centre, with the CIHEAM-IAMM and other partners, further developed the FSSIM model of the European Commission for application in developing countries.

The FSSIM-Dev (Farm System Simulator for Developing Countries) model is a bio-economic farm household optimisation model, with a first application to Sierra Leone (Louhichi et al., 2013). A household module has been added to the modular structure of FSSIM. Production, and related environmental outcomes, as well as food consumption are outputs of the model. Conditionally on the quality of the data about the environmental impacts associated with each production activity, and about food consumption and associated nutritional intakes entered and generated out of the model, such a model could assess the farming practices best suited to improve different sets of nutrition and/or biodiversity indicators and the associated trade-offs. In a normative approach, this approach could help define optimal combinations of activities and resulting diets. In a more positive approach, it could identify through simulation analysis the factors more likely to help attain some of these optimal combinations.

2.4 - Conclusions

A wider deployment of agricultural biodiversity is key for the sustainable delivery of a more secure and nutritious food supply. The importance of nutrient diversity for human wellbeing calls for dietary diversification. However, the quality of nutritional supply and human health are in danger because of losses in biodiversity. Biodiversity benefits affect social–ecological systems all along the food value chain, from agricultural activities, food processing and consumption patterns to nutrition and health status. There is a call for system approaches to capture the dynamic processes between and within the food system activities, nutrition and health, and environmental outcomes. Computational complex systems modelling techniques aim at capturing the co-evolution of human and biological systems, and the complexity of human decision-making (Hammond and Dube, 2012). They allow exploring key processes and outcomes of the analysed systems for food and nutrition security, delivering innovative and deeper insights at the environmental level. Food consumption behaviours play a central role in driving us towards the sustainable food system. Understanding how food supply translates in nutrition-adequate consumption patterns, together with capturing choice determinants and underlying consumer's perceptions of environment-friendly practices, are crucial to help guide changes towards sustainable uses of resources for nutrition. Food consumption behaviour has not attracted enough attention from the sustainability community. Further research requires knowledge of the concepts and insights from a wide range of disciplines to tackle the complexity and diversity of influences at work in food choices. Joint efforts are needed in addressing food and nutrition security through a multidisciplinary and multisectoral approach to social–ecological systems.

Preface to Chapter 3

Recurrent food crises and climate change, along with habitat loss and micronutrient deficiencies are global issues of critical importance that have pushed food security and environmental sustainability to the top of the political agenda. Analyses of the dynamic linkages between food consumption patterns and environmental concerns have recently received considerable attention from the international and scientific community. Using the lens of a broad sustainability approach, this chapter aims at developing a multidimensional framework to evaluate the sustainability of food systems and diets, applicable to countries of the Mediterranean region. Derived from natural disaster and sustainability sciences, a vulnerability approach, enhanced by inputs from the resilience literature, has been adapted to analyze the main issues related to food and nutrition security. Through causal factor analysis, the resulting conceptual framework improves the design of information systems or metrics assessing the interrelated environmental, economic, social and health dynamics of food systems.

Chapter 3

Sustainability and Food & Nutrition Security: A Vulnerability Assessment Framework for the Mediterranean Region[2]

[2] *This chapter is adapted from:*
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3.1 - Introduction

Over the past 25 years, the international and scientific community has repeatedly attempted to deal with the issue of sustainability. "Our Common Future" (United Nations, 1987), commonly known as the "Brundtland Report", argues that sustainable development should meet "the needs of the present without compromising the ability of future generations to meet their own needs". It stresses the necessity to implement economic, social, environmental and institutional progress that can be maintained over time. Worldwide concerns about sustainable development are also reflected in the global food security debate, which states that "Food security exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food which meets their dietary needs and food preferences for an active and healthy life" (FAO, 1996). The 1996 World Food Summit (WFS) identifies four main determinants of food security: food availability, accessibility to food, food utilization, and the stability over time of the three previous dimensions; depletion in any one of these leads to food insecurity.

The first crucial change from the supply-based food security concept of 1974 (United Nations, 1975) came with the access-related definition of food security (FAO, 1983; World Bank, 1986) using Sen's entitlements approach (Sen, 1981). Then, the nutrition approach guided the notion of utilization (Staatz, D'Agostino & Sundberg, 1990), highlighting the need for quality, including good and culturally accepted feeding practices, food safety and nutritional value. During the same period, Maxwell and Frankenberger (1992) sustain the theory that household access to sufficient and nutritious food at all times is key to food security. Building on the 1986 World Bank report "Poverty and hunger", the stability dimension, related to the temporal dynamics of food insecurity, was explicitly acknowledged.

Associating sustainable agriculture and food security, Speth (1993) suggests orientating development strategies towards the combined socio-economic-environment goal of sustainable food security.

Sustainable food security is actually the concept underpinning the 1996's definition of the WFS where environmental and social issues were further stressed, especially for climatic risks, water availability, biodiversity losses and cultural food preferences. The term of "sustainable food security" was already coined in March

1987 in the Brundtland Report. Yet in 1983 Swaminathan was among the first to point out the need for an ecological foundation to food security "to protect basic life-support systems of land, water, flora, fauna, and the atmosphere" (Swaminathan, 1983, p. 37). In 1987, Swaminathan reaffirmed the sustainable food security concept, extending it to encompass both to nutritional and water issues, while Gussow and Clancy (1986) were the first to use the term "sustainable diets" to define diets both healthy for the environment and humans.

The multiple interconnected dimensions of these two concerns – sustainable development and food & nutrition security – open new avenues for multidisciplinary research, as demonstrated by the emerging literature on the topic and the more recent related global events. The main conceptual outcome of the 2010 International Scientific Symposium on Biodiversity and Sustainable Diets is the definition of sustainable diets as "*those diets with low environmental impacts which contribute to food and nutrition security and to a healthy life for present and future generations. Sustainable diets are protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable; nutritionally adequate, safe and healthy while optimizing natural human resources*" (FAO & Bioversity International, 2012, p. 7).

It is clear from this definition that the issue of sustainability of diets closely refers to food and nutrition security. The sustainable diets definition establishes four main goals for the governance of a future sustainable food system: human health and nutrition, cultural acceptability, economic viability and environmental protection (Fanzo, Cogill & Mattei, 2012). It highlights some crucial elements such as the importance of biodiversity stocks not just for the agriculture and the environment, but also for adequacy to nutritional recommendations and cultural acceptability. The multiple conditions of sustainability clearly encompass several dimensions. These conditions refer to different sets of capital that allow flows of services to be maintained over time. Stiglitz, Sen and Fitoussi (2009) suggest that these welfare-producing services can be sustained over time when stocks of capital (natural, physical, human and social) are transferred to future generations.

The analysis of the sustainability of food security requires a shift towards a multidimensional vision (Pinstrup-Andersen, 2009), but also a transversal approach across the multiple activities leading to diets. Achieving both sustainability and food security requires more than focusing on agriculture or on markets or on household food baskets, but to look at the overall food system (Ingram, 2011). Sustainable food systems are key for assuring sustainable food security (FAO & Bioversity International, 2012), and they cannot be pursued in the absence of food and nutrition security (Buttriss & Riley, 2013). Food security and food system sustainability are then indispensable prerequisites to each other and they need to be jointly analyzed.

Policymakers and stakeholders play a key role in the governance of future sustainable food systems, at a different spatial scale. They need evidence-based scientific information to define policy and implement actions (Barrett, 2010). The aim of this chapter is to develop a conceptual framework, applied to the Mediterranean region, which links concepts, methods and metrics, for a multidimensional joint analysis of food and nutrition security and food system sustainability. Building on the resilience literature, the vulnerability approach (Turner et al., 2003) provides a systemic causal pathway to analyze the impacts of the main drivers of change on specific food security and nutrition outcomes. It allows understanding and assessing the conditions of sustainability of the food system. This chapter provides the conceptual background to develop metrics, relying on evidence-based scientific knowledge, to inform all stakeholders, particularly policymakers, on response interventions to major changes at national and regional scale, in order to maintain the ability of the system to provide food security and good nutrition over time, while taking into account environmental, social and economic constraints and assets.

We first introduce the Mediterranean context and briefly review the main issues related to food and nutrition security and food system sustainability in the region. Developed from natural disaster and sustainability sciences, the vulnerability conceptual framework is presented as a valid approach to capture and model food system sustainability. We then expose the associated metrics – or information system – to quantify vulnerability that integrates three essential components: exposure, sensitivity, and adaptive capacity (Turner et al., 2003). We finally discuss the utility of this approach with examples of its possible application to Mediterranean countries.

3.2 - Food Insecurity and Environmental Unsustainability: A joint regional analysis

Changes in dietary patterns and food insecurity

Globally, more than 2 billion people are food insecure, either undernourished, malnourished or overnourished (FAO, WFP & IFAD, 2012; Strang, 2009; WHO, 2013). Concurrently, there is consensus among the international and scientific community on the non-sustainability of the western agrofood system, in terms of its impacts on natural resources and ecosystems, and on human health with increasing prevalence of non-communicable diet-related diseases. The Mediterranean region has been identified as one of the main critical hotspots of environmental unsustainability due to intense human activity and agricultural exploitation (Capone, Lamaddalena, Lamberti, Elferchichi & El Bilali, 2012; Salvati, 2013). A large part of its population can also be considered food insecure. Using United Nations (UN) anthropometric and population composition data[3], out of a total population of about 500 million, it is possible to estimate that at least 215 million adults and children (44% of total population) are "qualitative and quantitative food-insecure" in the Mediterranean region[4,5]. The geographical zone represents an interesting testing area of study in which to carry out a multidimensional analysis of the inter-connected factors that characterize food insecurity and environmental unsustainability. In this section, we present a joint analysis of the current situation and show how both issues intersect.

On the supply side, all the dietary energy supplies (DES) of the Mediterranean countries[6] largely exceed the average dietary energy requirements. At the same time the majority of these countries are strongly dependent on imports, especially for

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[3] Data is not completely available for all Mediterranean countries.

[4] This count involves overweight and underweight adults (age > 20 years) and overweight, underweight, stunted and wasted children (age < 5 years) within the Mediterranean population. Available data at September 2013 were collected from: World Health Organization, Global Database on Child Growth and Malnutrition and Global Database on Body Mass Index; UN Department of Economic and Social Affairs – Population Division).

[5] In UN databases many of the cited statistics are not assessed in several Mediterranean countries: Child stunting, wasting and underweight are not assessed in Cyprus, France, Greece, Israel, Italy, Lebanon, Malta, Portugal, Slovenia and Spain; Child wasting is not assessed in Algeria, Croatia, Morocco, and Turkey. Child stunting is not assessed in Turkey; Child overweight is not assessed in Croatia, Cyprus, France, Israel, Italy, Malta, Portugal and Serbia; Adults underweight is assessed just in France, Italy, Jordan, Malta, Portugal, Spain, Macedonia and Turkey. Adults' overweight is assessed in all Mediterranean countries.

[6] Except for the Occupied Palestinian Territories.

cereals (except France and Turkey). Furthermore, the share of DES derived from cereals is still considerably high (Egypt 65%, Morocco 57%, Algeria 55%, Tunisia 51%, Libya 49%, Turkey 48%) (FAOSTAT 2009, data available in November 2013)[7]. This cereal-centered dependency can lead to a regional and national vulnerability. In particular, it occurs at the expense of middle- and low-income groups, and of the national government expenditure. For example, bread subsidies, amounting to US$ 2.5 billion per year, were introduced in Egypt in 2008 (FAO, 2012). It is also necessary to consider food price volatility, in particular for cereals, as it affects consumers' capabilities to access food. Other related socio-economic factors also determine access to food, such as adult literacy, which is still low in some countries (Libya 89%, Algeria 73%, Egypt 72%, Morocco 56%) (UNESCO, data available in November 2013). As for the utilization dimension of food security, nutritional value and food safety remain critical issues. Infant mortality (Morocco 28‰, Algeria 26‰, Egypt 18‰, Tunisia 14‰, Albania 13‰, Turkey 12‰), child stunting (Egypt 31%, Syria 27%, Albania 23%, Morocco 23%, Libya 21%, Algeria 16%, Tunisia 9%), wasting (Morocco 11%, Syria 11%, Albania 9%, Egypt 8%, Libya 6%, Algeria 4%, Tunisia 3%) and underweight (Morocco 10%, Syria 10%, Egypt 7%, Albania 6%, Libya 6%, Algeria 4%, Tunisia 3%) are still considerably high (WHO, data available in November 2013). In addition to this, obesity and overweight are growing problems common to all the Mediterranean countries, both for adults and children. This double burden of malnutrition is manifest in Egypt with prevalence rates of 33% in adult obesity and 20% for child overweight, against 31% for child stunting. Overweight and obesity are also risk factors in cardiovascular diseases, which contribute to 42% of all deaths in the Mediterranean (Rastoin & Cheriet, 2010).

Obesity is closely linked to dietary behavior and socio-economic determinants, but also to agricultural policies, production systems and food chain characteristics (Delpeuch, Maire, Monnier & Holdsworth, 2009). In the Northern Mediterranean countries, these diet-related pathologies are the symptoms of an overconsumption of meat (especially red meat), dairy products and eggs (Padilla, 2008), with a tendency towards overconsumption of energy-rich and nutrient-poor foods (Darmon & Soler, 2013). In Southern Mediterranean, the double burden phenomenon represents the chronic phase of a nutrition transition. Statistics show a change of diet towards a

[7] The share of different commodities in total supply is used also as a proxy metric of dietary diversity, which is strictly linked to health and nutrition factors.

regime that is richer in animal proteins and fats, at the expense of dietary diversity and food providing important micronutrients (Popkin, 2003). At the same time, supply shortage and struggle for access to food remain persistent for large cohorts of individuals. Another feature of the nutrition transition in the Southern Mediterranean countries is the change in the share of energy sources derived from added sugars, with increased intake of simple carbohydrates and refined sugars (Drewnowski & Popkin, 1997) and, in particular, a sharp increase in levels of simple sugar consumption through processed industrial products (drinks, biscuits, desserts, etc.) (Padilla, 2008).

Hence nutrition transition and malconsumption[i] are the two major food phenomena leading to diet-related diseases in the Mediterranean. Nutrient-poor "pseudo foods" (Winson, 2004) with high levels of vegetable oils, animal fats, sugar and salt permeate the global food system (Popkin, 2005). Long-established dietary patterns and traditions using local staples are being replaced with western-style highly processed products (Pingali, 2006). This is the case in emerging economies that are experiencing several phenomena simultaneously, such as increased urbanization, household income growth, greater market penetration by foreign brands, global supermarket and food service chains, expansion of advertising and mass media, and highly competitive prices (Sage, 2012). These dynamics lead to qualitative changes in diets and thus new food security issues, together with changes in lifestyle and work environment, with a growing tendency towards sedentary jobs and physical activity increasingly being limited to leisure time (Gil, Gracia & Pérez, 1995). These changes in diets contribute, as causal factors, to the rising incidence of nutrition-related non-communicable diseases, such as heart disease, cancer, diabetes and obesity.

The associated issue of environmental unsustainability

These dietary changes and the increasing incidence of related diseases coincide with major transformations in the agricultural and food systems, which have become more global and complex. These evolutions in food behavior patterns and in industrial production and processing have joint social, economic and environmental impacts. It is a fact that the nutritional characteristics of diets are directly related to environmental conditions, which are consequences of the production system associated with current food consumption patterns. The question is to understand to which extent. The environmental impact of the current agrofood system is a widely debated question. Darmon and Soler (2013), for instance, observe a positive correlation between calorie intake and greenhouse gas emissions. In any case, it should be noted that the Mediterranean agrofood sector represents 25% of the global Ecological Footprint of the region (Global Footprint Network, 2012).

The current shift from diverse farming systems to ecologically simplified ones, mainly based on cereals, contributes to micronutrient deficiency, poorly diversified diets and thus malnutrition in developed, as well as in developing countries (Frison, Smith, Johns, Cherfas & Eyzaguirre, 2006; Graham et al., 2007; Negin, Remans, Karuti & Fanzo, 2009; Remans et al., 2011; Welch & Graham, 1999). An important negative outcome of intensive production, in addition to environmental damage such as soil depletion and erosion, and pollution of surface and groundwater, is the narrowing of biodiversity base through the use of only the most profitable varieties. Many of the processes and much of the equipment used in the food industry have been developed to transform staple foods with specific characteristics (e.g. size, color group, quality category, etc.). As a consequence, despite an apparent diversity of the final products available on the market for consumers, genetic resources diversity tends to shrink. Current industrial production systems favor limited varieties and monocultures to the disadvantage of biological diversity (Esnouf, Russel & Bricas, 2013). The issue of biodiversity loss is related both to environmental concerns and to health and nutrition issues, because of its link with insufficient diet diversity, micronutrient deficiency, and unhealthy food habits (Burlingame, Charrondiere & Mouille, 2009). The importance of food variety and composition, especially in terms of genetic resources, is increasingly acknowledged. Differences in nutrients between varieties have a major impact on nutrient intakes; higher consumption of one variety over another can lead to adequacy or deficiency in certain micronutrients. For this reason, nutrition research looks at both the food composition and consumption dimensions (Burlingame et al., 2009). The alarming rate of biodiversity loss and ecosystem degradation, and the consequent negative impact on food and nutrition security, also provide strong reasons to reconsider the food systems and diet approaches. It is necessary to develop and promote strategies for sustainable food regimes, emphasizing the positive role of biodiversity to reverse or mitigate the phenomena that cogenerate negative effects on human nutrition and health (Burlingame, Charrondiere, Dernini, Stadlmayr & Mondovì, 2012). However, measuring food and nutritional biodiversity is a difficult task; the INFOODS network developed metrics that need a large amount of data, which are difficult to collect.

The environment throughout the entire geographic area of the Mediterranean is at risk, threatened by the intensive exploitation of its natural resources, particularly water (Lutter & Schnepf, 2011; Roson & Sartori, 2010; UNEP, 2006). Considering the increasing issue of drought in the region, the intensification of water requirements for food is a major concern (Capone et al., 2012). The high water demand of the Mediterranean food system reveals a deficit in terms of virtual water exchange for agrofood products (Mekonnen & Hoekstra, 2011)[8]. Water consumption trends are directly related to food consumption patterns since food products bring with them an internal quantity of water that differs by foodstuff origin, quality and quantity. Water requirements for plant and animal products vary widely. Red meat and dairy products, for example, are considered highly water-consuming compared to crop production. Thus, the quantity and types of food demanded strongly implicate the extent of water allocated and used for agriculture and related production activities (Lundqvist, de Fraiture & Molden, 2008). Water consumption is therefore also connected to nutritional composition of food consumed and strictly related to life habits and to drivers of change affecting the food system.

The relationship between unhealthy foods and highly environment-impacting foodstuff is tentatively captured by the Barilla Center's Double Pyramid (Barilla Center for Food and Nutrition, 2010). Some argue that the more frequently recommended healthy food corresponds also to lowest environment impacting products, and vice versa. Consumption of red meat is, for example, often considered the heaviest variable affecting the sustainability of food systems and consumed in excessive amounts in developed countries (FAO, 2006; Lang, Dibb & Reddy, 2011). However, evidence is mixed with regard to the general alignment of environmental and nutritional recommendations. For instance, Vieux, Darmon, Touazi and Soler (2013) show that high nutritional quality is not always associated with low greenhouse gas emissions. Certainly no single food can encompass the wide range of

[8] The concept of virtual water clearly depicts the global shifts of water embedded in products. Virtual water associates consumer goods to an amount of water needed to produce them. For instance the difference in water consumption was measured between a diet rich in meat (5400 liters virtual per day) or vegetarian (2600 liters) for American eaters (Hoekstra, 2002). In particular virtual water indicates the volume of freshwater used to produce a given good, counted at the place where the product was de facto produced (Hoekstra & Chapagain, 2008; Van Oel et al., 2009). The concept of virtual water reveals how much water is needed to produce different goods and services.

both nutritional and environmental recommendations, without even mentioning economic viability and social acceptability constraints. A myriad of factors affecting both actors and activities within the food system explain the nutritional and environmental outcomes of dietary behaviors. Providing a clearer picture of the circular dynamics between environmental, health, economic and social drivers can help not only to measure impacts or progress, but also to understand interactions, and thus aid decision making. We suggest tackling this complex challenge by applying the vulnerability framework to the changes affecting the agrofood system.

Building on Ingram (2011), we defend an approach to metrics, which switches not only from the "what we get" (food security outcome approach) to the "what we do" approach (food systems-activities approach) (p. 419), but which also considers the "what happens" side (food system-drivers interactions). The Mediterranean region presents several factors of change affecting food security and environmental sustainability. The multiple issues related to food insecurity and unsustainability that have been exposed above for the Mediterranean region can be analyzed from a multidimensional perspective, as a series of issues or hotspots of vulnerability of the different national agrofood systems, and integrated within a conceptual framework linking concepts, methods and metrics.

3.3 - Vulnerability for a multidimensional and dynamic system approach

Mechanics of change and sustainability

According to the definition of agro-ecosystem sustainability coined by Conway (1985), "Sustainability is the ability of a system to maintain productivity in spite of a major disturbance, such as caused by intensive stress or a large perturbation" (p. 35). Consistently with the literal English usage of the verb "to sustain", Hansen (1996) further interprets sustainability as a system's ability to continue through time. If sustainability is the dynamic ability of a given system to maintain or enhance its essential outcomes over time and space, then the concept of vulnerability can provide the elements to understand the mechanisms affecting the activities of the system (Turner et al., 2003).

The United Nations Development Programme (UNDP) defines vulnerability as the "degree of loss to each element should a hazard of a given severity occur" (1994, p. 49), i.e. the extent to which an individual or system or geographic area is damaged in relation to a given change. Downing (1990) states that "Vulnerability is the composite of two prospects: risk of exposure and risk (or magnitude) of consequence" (p. 11). The exposure to hazardous events is different from the magnitude of the consequences that result from that exposure. The vulnerability approach further evolves with Turner et al., (2003), who established three main components to vulnerability: exposure, sensitivity and adaptive capacity. Adaptive – or copying – capacity corresponds to the responses that it is possible to implement. The theoretical basis for this evolution is to be found essentially in the theory of abilities and capabilities (Sen, 1981).

The vulnerability assessment is today widely acknowledged as composed of three dimensions (Adger, 2000, 2006; Adger & Vincent, 2005; Allison et al., 2009; Cinner et al., 2011; Gallopin, 2006; Kelly & Adger, 2000; IPCC, 2001; Grafton, 2010; Smit & Wandel, 2006): exposure and sensitivity to single or multiple stressors, and the adaptive capacity to cope with these. Hughes et al. (2012) adopted such a conceptual framework to quantify the anthropic effects on coral reefs and national food security, developing a national-level vulnerability index. In the case of the fresh fruit and vegetable value chains, the vulnerability approach was adopted to assess the strengths and weaknesses of Mediterranean production zones facing an increasing competition from South East Mediterranean countries (Rastoin, Ayadi & Montingaud, 2007). The aim was to build an inter-regional diagnostic comparison by means of a Regional Vulnerability Index (RVI).

Vulnerability is a relative measure, and the exposure of individuals/systems/regions is related to their specific conditions. Similarly, the magnitude of the consequences from this exposure is linked to these particular characteristics and their associated sensitivity. Most adaptive capacity analyses tend to be specific to a place and context while linked across scales (Turner et al., 2003), and vulnerability is most frequently assessed at national levels (Allison et al., 2009; Brooks, Adger & Kelly, 2005; Pelling & Uitto, 2001). The benefits of assessing vulnerability at the national level are that results can influence national-level policy responses and adaptive management strategies (Hughes et al., 2012).

A causal-factor approach

One key conceptual element is a clear distinction between causal events and outcomes (Dilley & Boudreau, 2001). Following the introduction by Sen (1981) of the notion of accessibility beyond availability as a main determinant of famine, the analysis of food security shifted from a study of the sole natural causes to the inclusion of societal causes (Blaikie, Cannon, Davis & Wisner, 1994). The vulnerability framework was indicated to describe and assess the multifaceted socioeconomic determinants of famine (Borton & Shoham, 1991; Maxwell & Frankenberger, 1992; Middleton & O'Keefe, 1998; Ribot, 1995; Swift, 1989) (as cited in Dilley & Boudreau, 2001). The vulnerability approach, based on natural disaster assessment, was then transposed to societal causes for the analysis of food insecurity. In particular, Chambers (1989) and Downing (1990) made considerable efforts in converting Sen's analysis into assessment methods. The main result was the expression "vulnerability to famine" (p. 233), which became widely popular. It was understood in direct relation to the final outcome. However, Downing (1990) clearly stated that vulnerability is "a relative measure, for a given population or region, of the underlying factors that influence exposure to famine and predisposition to the consequences of famine" (p. 18), aiming at identifying elements for a causal factor analysis.

In the food security context, the Food and Agriculture Organization (FAO) specified that vulnerability is the relationship between risks, resulting shocks and resilience to these (FAO, 2004). The coupled risk-shock component affects population wellbeing and food security, while resilience concerns the strategies implemented to mitigate the impact of the shocks. Vulnerability is understood as directly correlated to the impact of shocks and is inversely correlated to resilience (FAO, 2004). While the natural disaster management approach to vulnerability involved the identification of a degree of damage on populations or economic assets, food security specialists applied vulnerability to measure the intensity of the state of food insecurity or famine (Dilley & Boudreau, 2001). Hence, it is possible to define the FAO vulnerability approach to food security analysis as a direct "outcome approach", whilst the natural disaster method is rather a "causal factor approach", describing the interactions leading to the final outcomes.

Given the wide and complex sequence of phenomena involved in food insecurity and environmental unsustainability, the causal factor specification can also help to distinguish several vulnerabilities of specific issues or outcomes. It allows a dynamic analysis of the particular issues of vulnerability, instead of a static identification of vulnerability to a broad and general final outcome. Furthermore, a broad understanding of vulnerability on wide range of sectors or issues would not be sufficiently focused to implement actions (Ionescu, Klein, Hinkel, Kumar & Klein, 2009; Leurs, 2005). Regarding the multidimensionality of the concepts of food security and sustainability, assessments based on one element or one dimension are no longer considered sufficient (Aubin, Donnars, Supkova & Dorin, 2013). There is a rising call for new types of systems analysis and modeling tools (Nicholson et al., 2009). The fragmentation of the broad concept of vulnerability in an integrated general framework is a first response to this need.

Vulnerability has evolved as a term of art and a conceptual framework to implement assessment methods in different research areas, such as climate impact analysis (Timmerman, 1981), disaster management (UNDRO, 1979), food security (Chambers, 1989; Dilley & Boudreau, 2001), and sustainability science (Turner et al., 2003). The analysis of vulnerability can provide a conceptual and methodological approach to the understanding of sustainability. It offers a logical conceptual basis and method upon which to build a modeling causal framework that raises awareness on: vulnerable people or entities to shocks; how and where the shocks modified the living conditions; which are the response strategies; the identification of the multiple metrics that assess the phenomena. Additionally, Turner et al. (2003) referred to vulnerability assessment as a coupled human-environment system approach and reaffirmed the role of sustainability and global change science in improving the bonds between the science problem and decision-making needs.

3.4 - Methodological steps for the assessment of Vulnerability

A composite indicator

A joint assessment of food insecurity and environmental unsustainability is strictly linked to the identification of a methodological framework functioning as an architectural net. In Rastoin et al. (2007), Cinner et al. (2011), Hughes et al. (2012), as in the vulnerability composite index of food insecurity in Manarolla (1989), vulnerability is calculated through multidimensional score systems. The vulnerability causal framework is modeled through three dimensions: exposure, sensitivity and adaptive capacity.

Exposure

Building on sustainability and natural disaster sciences, exposure is considered as the degree to which a system experiences environmental or socio-political stress (Adger, 2006), including frequency, magnitude, duration and the areal extent of the hazard (Burton, Kates & White, 1993). It can thus be interpreted as the likelihood of experiencing stress or perturbations (Downing, 1990). For the purpose of this work, we define exposure as the degree to which a system or a country is subjected to changes directly causing or indirectly prompting food insecurity and environmental unsustainability. For instance, in a context of dependency on cereal imports, the share of cereals in total consumption can indicate the degree of exposure to cereal price volatility. Exposure is directly correlated with vulnerability.

Sensitivity

Sensitivity can be defined as the consequence of the exposure to a stress. It is the degree to which a system is modified or affected by the perturbations or the outcome of an unwanted event to which the system is exposed (Adger, 2006). It can be understood as the likelihood of experiencing different magnitudes of consequences of exposure to a stress or perturbation (Downing, 1990). For instance, price elasticities for cereals may represent the sensitivity to fluctuating international cereal prices, since they represent the effective impact of the exposure. Indicators of sensitivity are generally measuring impacts. As for exposure, sensitivity is directly correlated with vulnerability.

Adaptive capacity and resilience

The third component of vulnerability, related to adaptive capacity, was defined as the potential of the system to respond to changes (Adger, Brooks, Bentham, Agnew & Eriksen. 2004; Burton, Huq, Lim, Pilifosova & Schipper, 2002; IPCC, 2001). Cinner et al. (2012) and Hughes et al. (2012) propose to disaggregate adaptive capacity into several categories such as assets, flexibility, learning, and social organization. In physics, resilience is the resistance of an object to a given shock. According to Rastoin et al. (2007), the concept of resilience is applicable to biology and human sciences as the resistance of an individual or a community to an external stress. For instance, when coupled, exposure and sensitivity negatively affect people's welfare and food security status. In the case of food price volatility, resilience contains all the coping strategies that can be implemented or are already implemented to avoid exposure to risks and minimize impact sensitivity to the shock, in order to overcome detrimental effects. National and global institutions, for instance, by means of food price protection policies, safety nets and subsidies, can encourage these strategies.

In an institutional context, resilience can represent stakeholders' reactive capacity to cope with changes. Stakeholders can respond with coping and adapting strategies to rule economic, finance, social institutional changes (North, 1991). Sen (1985) similarly identifies for individuals the capacity to manage opportunities deriving from risk effects, by means of the concept of capabilities. The stakeholders, searching in their natural, human, physical and social assets, take the opportunity of the environmental changes, transforming these resources in capabilities, which allows overcoming the shocks' impacts and to be prepared for the next risks. For these characteristics that identify resilience (or adaptive capacity), the concept is often associated with sustainability (Conway, 1985; Strunz, 2012). While vulnerability is directly associated with risks and shocks impacts, resilience is inversely correlated with vulnerability (FAO, 2004). People who overcome negative impacts of changes (and end up in an even better situation) would be resilient; those suffering from the effects of the modifications would be considered as vulnerable (Rastoin et al., 2007).

Calculating a Vulnerability score

In Rastoin et al. (2007), the estimation method is based on the capabilities approach; vulnerability is then assessed solely on the one component of adaptive capacity/resilience. In a more general framework this approach could be also associated with the exposure and sensitivity dimensions. Cinner et al. (2011) and Hughes et al. (2012) calculate vulnerability as Exposure + Sensitivity – Adaptive Capacity (Figure 3). Lower levels of the final score indicate lower level of vulnerability. Following the original structure designed by Hughes et al. (2012), keeping the same logical sequence of signs, Figure 3 outlines several *n* vulnerabilities. This specification of *n* different vulnerabilities of different issues to different drivers of change, aims to capture the multidimensional feature of sustainability.

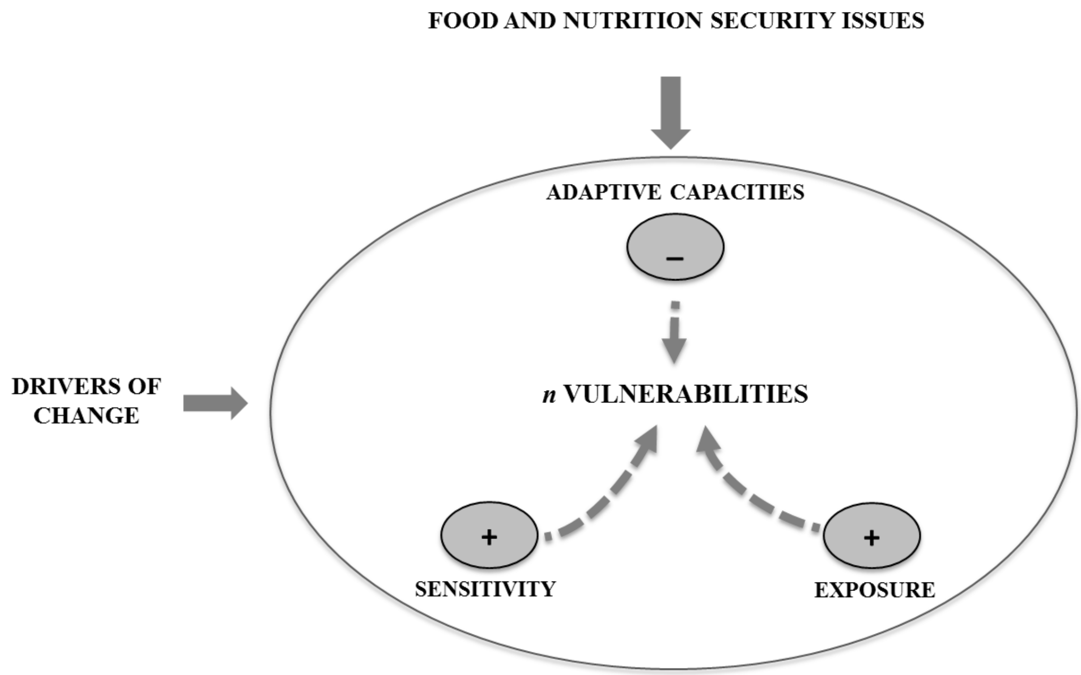

Figure 3 Calculation of Vulnerability (Adapted from Hughes et al., 2012)

The order and the signs used for the methods of calculation of vulnerability, define the relationships between the three components. However, in a metric-identifying approach, the indicators come from different sources and disciplines, and are expressed in different units of measurement. Index values then need to be standardized or normalized. In many cases (Cinner et al., 2011; Hughes et al., 2012; The Economist Intelligence Unit, 2013), data normalization is based on minimum and maximum values in the dataset, and places on a scale from 0 to 1 (from 0 to 100 for the GFSI, 2012) using the typical normalization method "min-max" (Adger & Vincent, 2005; OECD, 2008):

$$i(X) = (X - Xmin)/(Xmax - Xmin)$$

In this formula Xmin and Xmax are, respectively, the lowest and highest values for any given indicator. The normalized value is then transformed from a 0 to 1 value to make it directly comparable with other indicators. This means that the indicator with the highest raw data value will score 1, while the lowest will score 0.

In the examples referred to, the indicator scores are normalized and then aggregated across categories to enable a comparison of broader concepts across countries. Normalization rebases the raw indicator data to a common unit so that it can be aggregated.

Finally, in our specific case the *n* particular vulnerabilities will be calculated following this formula:

$$V = [(E – E\text{min} / E\text{max} – E\text{min}) + (S – S\text{min} / S\text{max} – S\text{min}) – (AC – AC\text{min} / AC\text{max} – AC\text{min})].$$

Where V = vulnerability, E = exposure, S = sensitivity and AC = adaptive capacity.

Another issue that has to be considered is the quantitative relevance, or weight, that is associated with the different components. Different metric systems often rely on equal weights, leaving to policymakers, practitioners and stakeholders the opportunity to apply a goal- or priority-oriented weighting system (Saaty, 1986; Hammond et al., 1999; McClanahan et al., 2008; The Economist Intelligence Unit, 2013).

Based on this approach, it would be possible to rank the Mediterranean countries in relation to their exposure, sensitivity and adaptive capacity *vis-à-vis* changes affecting agrofood systems in their food and nutrition security outcomes.

3.5 - Discussion of the approach

Metrics, analysis and prospective

The vulnerability approach stresses the need for methods and metrics that do not just express final results or outcomes, but provides a system of information that can be interpreted in a dynamic framework modeling interactions between different drivers. In particular, the vulnerability framework can be disaggregated in several dimensions according to the different drivers of change considered: vulnerability to climate change, vulnerability to price volatility, vulnerability to demographic transformations, etc. The integrated fragmentation of the broad vulnerability into specific vulnerabilities represents a response to the lack of causal factor analysis.

As mentioned above, each specific vulnerability can be further broken down into exposure, sensitivity and adaptive capacity. However, both the sensitivity and adaptive capacity dimensions of the system have to be assessed according to specific outcomes or services provided by the food system that need to be maintained over time. For instance, access to food may be jeopardized in the short term by high food price volatility; however, food supply might not be affected in the same way or to the same extent. Thus, problematic issues or hotspots, related to the agrofood system and local context, need to be specified. Three stages of causal factor analysis can be established through the vulnerability framework. In a nutshell, the framework allows organizing evidence-based information and aiding decision-making by clarifying sequential dynamics, while allowing for prospective or forward-looking analysis.

Therefore, it is important to define issues and challenges of food security and sustainability before choosing assessment methods (Aubin et al., 2013). The qualitative identification of the problematic issues, and then of the variables to assess vulnerability, can be obtained through a hierarchical analysis (Rastoin et al., 2007), previous field observations (Cinner et al., 2011; Hughes et al., 2012), a literature review and expert consultation, and using statistical methods such as Principal Components Analysis (Jolliffe, 1986).

The vulnerability framework can lead, for example through participatory methods, to the identification of a system of indicators and appropriate metrics, offering a method to capture complexity and interconnectedness between phenomena (Dilley & Boudreau, 2001; Turner et al., 2003). Furthermore, since indicators inform action (Barrett, 2010), they are essential to establish the communicative link between science and policymakers. One essential aim of the vulnerability analysis remains in the identification of the response opportunities for decision-making (Dilley & Boudreau, 2001; Turner et al., 2003; Rastoin et al., 2007).

To summarize, several functions can be attributed to the vulnerability approach such as: a holistic and novel assessment framework and a dynamic tool for sustainability sciences; a geographical-based approach involving the participation of local stakeholders; a multiple factor analysis allowing interdisciplinary research on complex and systemic phenomena; a scheme to conceptualize and develop metrics, in a system of information and response opportunities for decision making; a methodology to draw evidence-based knowledge; a predictive framework to anticipate consequences of hazards and changes (Watts & Bohle, 1993; Dilley & Boudreau, 2001; Turner et al., 2003; Adger, 2006; Fussel, 2006; Rastoin et al., 2007; Locatelli et al., 2008; Sonwa, Somorin, Jum, Bele, & Nkem, 2012). The main advantages of a vulnerability approach to the analysis of sustainability of food system activities are summarized in Table 1.

Table 1 Advantages of a vulnerability approach

Developing Metrics		
1.	Providing information and interpretation of the phenomena for decision making	(Dilley & Boudreau, 2001; Turner et al., 2003; Adger, 2006; Rastoin et al., 2007; Sonwa et al., 2012)
2.	Identifying complexity and interconnectedness of the phenomena	(Watts & Bohle, 1993; Dilley & Boudreau, 2001; Turner et al., 2003)
3.	Increasing scientific knowledge through vulnerability assessment	(Sonwa et al., 2012; Fussel, 2006; Locatelli et al., 2008)
Analysis		
4.	Allowing information analysis through quantitative and qualitative data and novel methods	(Turner et al., 2003)
5.	Allowing the multiple factor analysis for an interdisciplinary understanding of vulnerability	(Adger, 2006)
6.	Providing a dynamic tool applied to Sustainability science	(Turner et al., 2003)
Prospective		
7.	Further opening the causal interpretation rather than analyzing just the final outcomes of a phenomenon	(Dilley & Boudreau, 2001)
8.	Representing the opportunity to involve regional stakeholders in a place-based analysis and collaborative assessment (geographical approach)	(Turner et al., 2003)
9.	Anticipating and predicting new hazards and changes	(Dilley & Boudreau, 2001; Turner et al., 2003; Adger, 2006; Rastoin et al., 2007)

Identifying issues and dealing with multidimensionality

Limits to this conceptual approach depend strongly on the level of accuracy of the application. The main risk is the lack of a genuine causal factors analysis that can be avoided by disentangling the multiple vulnerabilities and their components. Thus, one crucial element in the application of the vulnerability approach resides in the level of accuracy in defining the problematic issues that are, in our specific case, driven by nutrition and food security concerns of the agrofood system.

Furthermore, scholars and practitioners highly focused in one specific scientific discipline may be skeptical with regard to the large amount of variables. However, the development of a multidimensional metrics framework can open a stimulating scientific debate involving experiences from several disciplines and feed the scientific knowledge base. Indeed, as observed in sustainability science and resilience thinking, inter- and trans-disciplinary communication is strictly linked to problem solving – instead of puzzle-solving –and related to participative creativity instead of dogmatism (Strunz, 2012). So, the development of the framework aims to create a flexible tool that can be adapted and modeled (as for a weighting system) to different users' and to different policy purposes related to nutrition and food security concerns. The involvement of the stakeholders is key to building up the framework and to assigning hierarchy to the indicators (Aubin et al., 2013).

In conclusion this scheme provides a multidimensional vulnerability framework to jointly assess nutrition and food insecurity and unsustainability. Starting from a specific geographical region, it represents a tool for policymakers. The Mediterranean geographical area, as a physical space where several environmental, social and economic and nutrition hotspots of vulnerability persist over time, offers a first case of application. The last subsection presents an analysis of some representative interactions between drivers of change, and food and nutrition security issues, together with the description of the resulting exposure, sensitivity and adaptive capacity.

Examples of application

Application of the vulnerability assessment framework requires specifying the context and the issues of concern. These can be identified by literature review or participative expert consultation. The analysis of each specific issue or hotspot of vulnerability (of a given geographical area) allows us to establish from which point of the causal sequence of phenomena, the components of exposure, sensitivity and adaptive capacity can be applied.

For the sake of illustration, we provide three examples of how to apply the vulnerability model to the specific geographical Mediterranean region. Given the nutrition and food security-driven perspective of this work, three main *issues* critical to the food system, namely supply, accessibility and nutritional value, are assessed, considering the three components of vulnerability. Each issue is analyzed against three different landscape *drivers* of change, respectively climate change, price volatility and nutritional transition and changing consumption patterns. This selection of driver/issue combinations, restricted to three for the sake of illustration, does not presume that the drivers cannot have impacts on several issues.

Food supply-related vulnerability to climate change.

National food supply rests on food production, stocks and imports (minus exports). It relies also on quantities used from feed, seeds and transformation. Depending on the agrofood policy strategies and on their financial system conditions, a national food system can be vulnerable because of several factors or drivers affecting food supply. The conceptual model provides an approach that develops a series of questions. A pertinent question can be: To which extent are the Mediterranean countries vulnerable to climate change in order to supply sufficient food commodities?

Given the crucial issue around water supply in the Mediterranean region, geographical indicators of the availability and quality of water can be considered a relevant measure of the exposure of a national (or a sub-national) food system to climate change in terms of provisioning of food. Consequently, sensitivity to this exposure can be expressed according to the specific level of consumption of water-demanding commodities by the households or the agro-industry. In response, agrobiodiversity could be an indicator of adaptive capacity to climate change, based on the assumption that biodiversity increases the stocks of crop material to draw upon to select or develop more drought-resistant crops. Ability to import from less exposed agricultural systems to climate change might be another indication of adaptive capacity.

Food accessibility-related vulnerability to international price volatility.

Food accessibility involves both physical access and affordability for individuals to adequate resource of food. A research question that emerges can be the following: To which extent are the Mediterranean countries vulnerable, considering their economic constraints, biophysical conditions and social habits, in their access to adequate food in the face of high price volatility? Given the high cereal import dependency of some Mediterranean countries (for human consumption, industry demand and animal feeding), exposure could be assessed by considering the caloric share of cereals in a representative household's food basket: The more cereals consumed, the higher the exposure for import-dependent countries. Price elasticities for cereals might offer a proxy for countries' sensitivity to fluctuating international cereal prices. Conversely, analyzing food consumption patterns, and households' capacity to shift towards cheaper or locally available food, while meeting the same caloric and nutritional requirements, may indicate strong adaptive capacities. Cross-price elasticities illustrate substitution possibilities. Countries can enhance this adaptive capacity by implementing food policies that diversify supply sources, by acting directly on food prices (e.g. subsidies), by providing social nets for the population (e.g. food stamps) or promoting diversity in consumption patterns.

Nutritional quality-related vulnerability to nutritional transition and changing consumption patterns.

Utilization encompasses all the factors related to how food is consumed and involves quality elements. In a nutrition-driven approach we consider also nutritional values of foods and adequacy of diets to nutrient recommendations. Therefore, the research question in our specific context can be the following: In which way and to which extent are the Mediterranean countries vulnerable, considering nutritional value and nutrient adequacy, to nutritional transition and changing consumption patterns?

Over the past fifty years the Mediterranean region has undergone important structural demographic and spatial transformations with an increasing share of its population now located in urban centers. Urbanization trends can be suggested as a proxy for exposure to changing food consumption habits, on the assumption that urban and rural consumption patterns are significantly different. Correlated with urbanization, industry and labor structures can be selected to indicate to which extent Mediterranean countries are exposed to nutritional transition. Subsequently, countries and populations manifest sensitivity to these exposures with critical data on the prevalence of health problems directly related to diet, such as obesity or cardio-vascular diseases. Governments, policymakers and individuals can implement a set of tools to enhance adaptive capacity, such as ensuring an efficient health system, improving education and promoting food and healthy eating and lifestyle habits, guiding consumption patterns, and raising awareness on these issues within institutions and the private sector.

3.6 - Conclusions

While securing food security is considered a global priority, there is contemporary widespread consensus about the importance of sustainability as a goal for food systems. This chapter provides a conceptual hierarchical framework for modeling the complex relationships between food and nutrition security and sustainability. It initially analyzed the internationally acknowledged concepts of sustainable development and food security, describing the interconnectedness between them that recent notions such as sustainable food security or sustainable diets try to capture.

Relying on an approach of the concept of sustainability as a system property allowing a desirable state to be "sustained" over generations, assessment methodologies should reflect the conditions of a system from a holistic and dynamic perspective. Calling on elements from the vulnerability and resilience literature, the proposed framework sequentially disentangles the exposure, sensitivity and copying/adaptive capacities of a specific food system to identified stressors or drivers of change jeopardizing critical food and nutrition security outcomes.

This approach entails also the assessment of sustainability with regard to a suitable temporal and spatial scale. Drivers affecting the sustainability of the food systems have multiple origins. The proposed framework hierarchically clarifies the different scale at which drivers and issues interact in a circular way with feedback loops. While suitable for expressing the global food-related concerns of a geographical region, it points out the need for assessment tools adapted to context-specific questions. Main data and general insights of the situation of the Mediterranean region help underline the main critical issues related to food and nutrition security facing the agro-food system in the region.

A quantitative method is proposed for assessing sustainability of food and nutrition outcomes by means of a precise correlation between the three components of exposure, sensitivity and adaptive capacities, which can ultimately be aggregated in a composite index. The joint assessment of food insecurity and unsustainability can be expressed through the language of vulnerability and resilience, as the degree to which a system is exposed and sensitive to dynamic phenomena, while considering its capability to respond and adapt. This approach provides the concepts fundamental to the development of potential indicators or metrics of sustainable diets and food systems, whose primary goal is to ensure food security and good nutrition for a healthy and active life.

Preface to Chapter 4

The processes underlying environmental, economic and social unsustainability derive in part from a shared food system. Building sustainable food systems has become a key endeavor to redirect our food systems and policies towards better-adjusted goals and improved societal welfare. Food systems act as complex social-ecological systems, involving multiple interactions between human and natural components. Policy needs to strengthen the perception of humanity and nature as interdependent and interacting. The systemic nature of these interactions calls for systems approaches and integrated assessment tools. Identifying and modeling the intrinsic properties of the food system that will ensure that its essential outcomes will be maintained or enhanced over time, across generations, can help organizations and governmental institutions track progress towards sustainability and set policies that encourage positive transformations. This chapter proposes a conceptual model that articulates crucial vulnerability and resilience factors to global environmental and socio-economic changes, postulating specific food and nutrition security issues as priority food systems' outcomes. Acknowledging the systemic dimension of sustainability, the approach allows considering causal factors dynamics. In a stepwise approach, a logical application is schematized to three Mediterranean countries, namely Spain, France and Italy.

Chapter 4

Modeling Sustainable Food Systems[9]

[9] *This chapter is adapted from:*
Prosperi P., Allen T. Modeling Sustainable Food Systems (*Submitted to a peer-reviewed scientific journal on December 2014*).

4.1 - Introduction

Sustainability has become a guiding principle and main goal for human development. Environmental degradation, social distress and economic fluctuation are worldwide concerns challenging conventional views on development and forcing reconsideration of our everyday behaviours. Rapid climate change has been occurring for the past few decades, and is predicted to continue and possibly accelerate (IPCC, 2012). Global biodiversity is declining, with substantial ongoing losses of populations, species and habitats (UNEP, 2012). Increasing land clearance for crop cultivation has been leading to habitat loss and may ultimately result in the loss of plant varieties. Policy needs to strengthen the perception of humanity and nature as interdependent and interacting. This requires revisiting our policies and behaviours, and developing adaptive management approaches acknowledging the systemic and dynamic nature of current changes.

Agriculture and food systems are at the center of the debates around sustainability. The processes underlying environmental, economic and social unsustainability derive in part from a shared food system. The increase in food supply has come with important trade-offs. Processes along the food chain, from agricultural production to food consumption, produce other outputs than food that are returned to the natural environment, such as pollution or waste. Food waste onlywould represent around 3-5% of global warming impacts, more than 20% of biodiversitypressure, and 30% of all of the world's agricultural land (EU, 2014). Meanwhile, 842 million people still suffer from undernourishment (FAO, 2013) while obesity has become a significant public health issue with 500 million obese adults (Finucane et al., 2011). Building sustainable food systemshas become a popular motto and key endeavor to redirect our food systems and policies towards better-adjusted goals and improved societal welfare.

A sustainable food systemcan be defined as one that "provides healthy food tomeet current food needs while maintaining healthy ecosystems that can alsoprovide food for generations to come, with minimal negative impact to theenvironment; encourages local production and distribution infrastructures;makes nutritious food available, accessible, and affordable to all; is humaneand just—protecting farmers and other workers, consumers, and communities" (Story et al., 2009). The food system is highly complex, driven by many economic, socio-cultural and environmental factors, which are both internal and external to its boundaries. The systemic nature of these interactions calls for systems approaches and integrated assessment tools to guide change.

Many intricately related factors are involved in getting food from farm to consumer, including the inputs, processes and outcomes of food systems, including nutrition and health. Food systems act as complex social-ecological systems, involving multiple interactions between human and natural components. Better understanding these drivers and how they interact to influence activities and outcomes of the food system, can help to improve public policies. Efforts to define, measure and model progress towards sustainability have led to the development of a variety of indicators and models that monitor and simulate (some of) these aspects of sustainability. In this chapter, we present an additional approach that consider vulnerability and resilience as the operating concepts to model the systemic factors that lead to final food systems' outcomes, such as food and nutrition security.

Food and nutrition security remains a crucial policy issue in every country and the current global crisis of malnutrition is an urgent concern both in developed and developing countries. The proponents of the "Sustainable Diet" agenda – a closely related concept highlighting the role of consumers in defining sustainable options – provide in particular a food and nutrition security-orientated perspective on the question of the sustainability of food systems (FAO/Bioversity, 2012; Johnston et al., 2014). Transforming the abstract concept of sustainability into descriptive objectives, this chapter proposes a conceptual model that articulates crucial vulnerability and resilience factors to global environmental and socio-economic changes in the Mediterranean region, postulating specific food and nutrition security issues as priority food systems' outcomes. Identifying and modeling the intrinsic properties of the food system that will ensure that its essential outcomes will be maintained or enhanced over time, across generations, can help organizations and governmental institutions track progress towards sustainability and set policies that will encourage positive transformations. The Latin Arc countries – Spain, France and Italy – have been selected as the study area for the biophysical and socioeconomic common features of this transnational area.

The first section of the chapter reviews the background and theory of sustainability, recalling that assessment exercises aim at identifying fundamental systemic properties. We discuss in particular the concepts of vulnerability and resilience proposed in social-ecological system frameworks as key concepts for sustainability assessment. Building on dynamic system theory, we then suggest a formal representation of the overall food system to structure its different elements; clarify the distinctions between input, state and output variables; and formalize the scale at which systems' dynamics are operating. In the third section, we present a stepwise application of the model, identifying specific drivers and issues for the Latin Arc and formulating explicit interactions. We finally motivate this approach in the discussion section.

4.2 - Identifying the fundamental sustainability properties of the food system

Sustainability as a system property

The multidimensional nature of sustainable development – which has to satisfy several economic development, social equity, and environmental protection goals – is generally emphasized. Proponents of sustainable agriculture have for instance proposed alternative farming practices, which are less environmentally impacting but also embedded in new sets of values and carrying other visions of organization in society. These renewed approaches to agriculture – such as organic farming, low-input agriculture, biodynamic agriculture, regenerative agriculture, permaculture, agroecology, etc. – are interesting crucial initiatives rooted in the ground. Yet, sustainability in agriculture cannot be defined per se by the simple adherence to one of these approaches; these are propositions of solutions towards sustainability.

The most frequently quoted definition of sustainability comes from Our Common Future, also known as the Brundtland Report (UN, 1987). Human development must meet "the needs of the present without compromising the ability of future generations to meet their own needs". This forward-looking imperative highlights the inter-generational and inter-temporal dimensions of sustainability, which thus infer that stewardship of both natural and human resources is of prime importance to ensure long-term development. When applied to the agricultural and food sector, Conway's frequently quoted definition of agro-ecosystem sustainability refers to "the ability of a system to maintain productivity in spite of a major disturbance, such as caused by intensive stress or a large perturbation" (Conway, 1985). Hansen (1996) further interprets sustainability as a system's ability to continue over time. The concept of agricultural and food sustainability refers to a property of a system, rather than an approach to agriculture. Only such an understanding can offer a way out of the logical flaw of judging the sustainability of approaches that have been defined in the first place as sustainable, and help assess the contribution of these approaches towards sustainability.

Sustainability is a property of a system that is open to interactions with the external. It is the dynamic preservation, over time, of the intrinsic identity of the system among perpetual change (Gallopin, 2003). Multiple factors influence the course of human-environment interactions, which are further complicated by the presence of co-evolving causal forces. Research in both the natural and social sciences uses the idea of a system to explain complex dynamics. A system is a network of multi variables that are connected to each other through causal relationships. Modern societies depend on complex systems to provide food (Fraser et al., 2005). Food systems encompass an array of activities from sowing through to waste disposal management,including production, processing, packaging and distributing, and retail and consumption (Ingram, 2009). Furthermore, global environmental and socioeconomic changes are occurring concurrently, affecting food activities. Food systems, in turn, have an impact on the environment, as activities and outcomes are also drivers of global environmental change, engendering feedback loops and cross-scale interactions. If assessing sustainability is about understanding these dynamics to gauge the ability of a system to maintain or enhance essential outcomes, it requires viewing the system as a whole. System thinking can be a useful approach to capture causal loops, where the effects of the last element influence the input of the first element. The coupled Human-Environment System or the Socio-Ecological System (SES) (Holling, 1996; Turner et al., 2003; Ericksen, 2008; Ostrom, 2009) approaches allow moving away from looking at isolated events and their causes, and looking at systems made up of interacting parts. The analysis and the assessment of the sustainability of the food system are here conducted through the application of an SES framework.

A social-ecological framework

SES frameworks originate from ecosystem management and Ecology. SESs can be defined as complex human–nature adaptive systems linked by dynamic processes and reciprocal feedback mechanisms, with a substantial exchange of energy and materials across boundaries (Berkes et al., 2001; Folke, 2006). A crucial challenge towards sustainability of food systems is the management of dynamics originating from both global and internal changes, and their different synergistic impacts on systems' outcomes. Only a better understanding of these processes will help estimating and forecasting resulting tradeoffs between human wellbeing and ecosystem services, economic performances and environmental impacts. Vulnerability and resilience have emerged in recent years as one of the principal SES framing concepts for research on global change (Donning, 2000; O'Brien and Leichenko, 2000; McCarty et al., 2001; Schroeter et al., 2005; Polsky et al., 2007; Turner et al., 2003). Vulnerability/resilience assessment and modeling are today acknowledged methods to explore sustainability of SES. There are several illustrations of approaches analyzing across food systems their vulnerability and resilience to global socioeconomic and biophysical changes in order to explore sustainability, highlighting key system processes and characteristics (Ericksen, 2008; Darnhofer et al., 2010; Allouche, 2011).

Vulnerability and resilience constitute different but overlapping research themes (Turner, 2010). Both address the consequences and the responses of system to social and/or environmental changes. Their continuing differences in approach to social-ecological dimensions of change are still in discussion (Miller et al., 2010). For a comprehensive review, please consult Alwang et al. (2001). Ericksen (2008) argues that the vulnerability approach "frames the consequences of environmental change for food systems in the context of socioeconomic and political change so as to understand the synergistic effects of the multiple stresses that interact with food systems, sometimes making these systems vulnerable" or not. The common ground of (almost) all approaches to vulnerability considers it as an "intrinsic characteristic of a system" at risk. The conditions and properties of the exposed system – or element of the system – are the crucial features to be identified and assessed (Birkmann, 2006). In the meantime, vulnerability deals also with features linked to capacities of the system to anticipate and cope with the impact of a change or hazard (Bohle, 2011). This allows flexibility in applying vulnerability for largely different elements, such as

structures and physical characteristics of buildings, ecosystems and environmental functions and services, but also communities and social groups.
The concept of resilience, originating in Ecology, is central to visualizing the dynamics of the coupled system. Resilience is interpreted differently by SES scholars but commonly recognized as a multi-attribute concept, composed of: i) ability to cope with disturbance or change and retain control of function and structure; ii) capacity to self-organize; and iii) capacity to learn and adapt (Walker et al., 2002; Berkes et al., 2003; Walker, 2004). Both vulnerability and resilience stress the need for methods and metrics that do not just express final results or outcomes, but provides a system of information that can be interpreted in a causal framework modeling interactions between different variables.

Building on Turner et al. (2003), the conceptualization of sustainability as the dynamic ability of a given system to maintain or enhance its essential outcomes over time, allows vulnerability and resilience theories to provide the elements to understand the mechanisms likely to affect activities within the system. The challenge for SES framework analysis here is to identify the pathways leading to vulnerability, and the characteristics and opportunities ensuring resilience of the food system in a context of change. Since contemporary food systems are characterized by cross-scale interactions and feedbacks across time and space and between the social and ecological components (Cash, 2006), efforts to rate how changes affect the performance of social, ecological and economic systems over time are key for the process towards sustainable development (Gallopin, 2003). At the same time, desired systemic properties can be expanded by investing specific components of systems (Marshke And Berkes, 2006). In particular, the vulnerability framework can be disaggregated in several dimensions according to different drivers of change: vulnerability to climate change, vulnerability to price volatility, vulnerability to demographic transformations, etc.

Vulnerability/Resilience for the analysis of food system sustainability

Vulnerability in SES depends on the stress to which a system is exposed, its sensitivity, and its adaptive capacity and resilience opportunities. In line with the internationally recognized IPCC definition, De Lange et al. (2010) states that "Vulnerability is generally considered as a function of exposure to a stressor, effect (also termed sensitivity or potential impact) and recovery potential (also termed resilience or adaptive capacity)". It proposes a clear and synthetic definition of vulnerability in its components that will be fundamental for the modeling exercise. Exposure refers to the existence or presence of elements in the system that are susceptible to be adversely affected by the occurrence of environmental or socio-political stresses (IPCC, 2012). It is a necessary but not sufficient first condition for a given system to experience stress or perturbations. Sensitivity is the degree to which a system is potentially affected by its exposure to a stress or perturbation (Adger, 2006). It can be understood as the potential magnitudes of consequences of being exposed (Downing, 1991). Indicators of sensitivity measure generally impacts. See Prosperi et al. (2014) for further clarification.

Recovery potential is composed of adaptive capacities and resilience opportunities. These are related to the potential of the system to respond to changes, including adaptation and transformation (IPCC, 2001; Burton et al., 2002; Adger et al., 2003). Adaptation captures the capacity of a system to learn and adjust to changing processes, and "continue developing within the current stability domain or basin of attraction" (Berkest et al., 2003; cited in Folke et al., 2010). Systems will absorb disturbances and retain their original structures and processes. Transformation has been defined as "the capacity to create a fundamentally new system when ecological, economic, or social structures make the existing system untenable" (Walker et al., 2004). Transformation is then necessary for the system to maintain its functionalities. Resilience is more specifically concerned with the ability of a system to "absorb shocks, to avoid crossing a threshold into an alternate and possibly irreversible new state, and to regenerate after disturbance" (Resilience Alliance, 2010). The ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions.

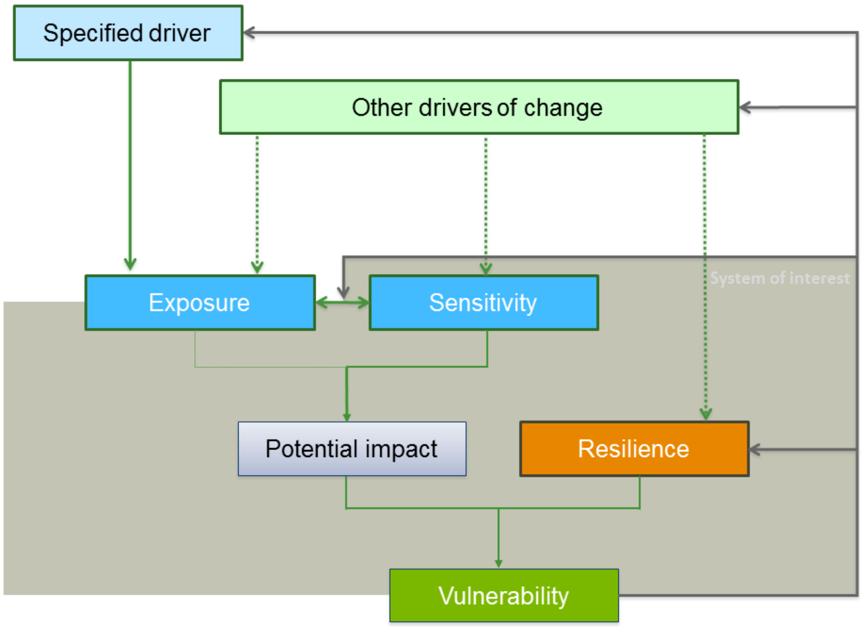

Figure 4 - A causal pathway (Adapted from Fussel and Klein, 2006)

Exposure refers to relational variables, i.e. elements that characterize the relationship between the system and its environment (Gallopin, 2006). It is the first point of contact between the stress or perturbation, and the system. Although commonly included in vulnerability (Chambers, 1989; Adger and Kelly, 1999; Turner et al., 2003; IPCC, 2011; Polsky and Eakin, 2011), exposure has recently been excluded from vulnerability in the last IPCC definition to actually align the understanding of vulnerability as a pure attribute of a system existing prior to and apart from the disturbance. In the earlier IPCC definitions, reference was indeed made as well to information on the change itself (e.g. its magnitude, rate of variation, duration, etc.), as well as on the presence of elements that are exposed. The question whether vulnerability is determined purely by the internal characteristics of a system, or whether it also depends on the likelihood that a system will encounter a particular hazard, is a long standing dispute (Brooks, 2003). We will consider here the conventional framework for vulnerability. The understanding of exposure as the first interface with a specific driver of change, helps differentiating it from the sensitivity or resilience components, which might be influenced by other drivers of change (Fussel, 2006).

When a food system fails to deliver food security or has the potential to do so in the face of a perturbation, the system can be considered to be vulnerable (Ericksen, 2008).

Foran et al. (2014) state that “The social-ecological system considers the human-environment interface as a coupled "system" where socio-economic and biophysical drivers of change interact to influence activities and outcomes, of the food system, that subsequently influence drivers of changes in a feedback loops dynamic”. Such systems can exhibit coherent behaviours. Constituting elements interact in a complex but lawful way. How can we account for the confluence of so many factors simultaneously? Resolving these issues is beyond the scope of traditional, linear, closed-system methods. Viewing food system sustainability from a dynamic systems perspective makes it possible to examine non-linear, complex, and reciprocally causal processes more explicitly. In the next section, we build on system thinking to identify the main variables to formalize and operationalize the abstract and multidimensional concept of sustainable food systems.

4.3 - Formalizing the food system as a dynamic system

What is a dynamic system?

The term “dynamic system” – or “dynamical system” – refers to a set of interacting elements that change over time. The first assumption of the dynamic approach is that evolving systems are complex, i.e. composed of many individual elements embedded within, and open to, a complex environment. These elements function together as collective units, producing outputs in relation to inputs through processes endogenous to the system. Changes in one variable will impact all other variables of the system, with possible lagged and multi-scale effects. It can include natural as well as human components. Outcomes thus emerge from the complex interactions among system elements and are not just the product of external causes.

The field of dynamic systems is vast. From initial work in cybernetics (Wiener, 1948; Ashby, 1956) and system theory (Kalman et al., 1962; Bertalanffy, 1968), system thinking grows directly from advance in Mathematics and Physics. Psychology also uses system-based approaches to explore human behavioral patterns. The more technical term “dynamic system modeling” refers to a class of mathematical equations that describe time-based systems with particular properties. Systems can be classified in different ways. System models can be either continuous or discrete. They can be linear or nonlinear, and time-invariant or time-variant. Systems can be static if its output depends only on its present input. On the contrary, a dynamic system requires past input to determine the system output.

The approach begins with defining problems dynamically, proceeds through modeling stages, then builds confidence in the model and its policy implications. As highlighted in the previous section, the idea of change is key to sustainability. Sustainability is about maintaining and/or enhancing essential functions or outcomes over time, taking into account environmental, social, and economic constraints and assets. Food system sustainability can be viewed as the ex ante assessment of potential change in its functioning, given external conditions and internal dialectic. More precisely, it aims at capturing (and protecting) the properties or features of the system crucial to supporting life, and food security in particular as the first reason for being of food systems (Haddad, 2013). This requires examining how the multicausality of dynamic processes within complex system such as the food system could help understand changes over time towards food security.

A mathematical representation

Modeling dynamic systems is about representing mathematically the dynamics between the inputs and outputs of the system of interest. Figure 5 shows a simplified graphical representation of a dynamic system such as the food system. It captures a closed-loop system, with feedback from outputs to inputs. A "controller" can monitor the output of the system by adjusting control variables u to achieve a specified response. When modeling input-output systems, in addition to an observed set of variables internal to the system that can be levers of action, external drivers can enter the model as inputs (Ionescu et al., 2009). If considered exposed to external influences, the system is said to be non-autonomous (Stankovski, 2014). Dynamical system can also be possibly perturbed by unobserved forces or noise. For the sake of simplicity, the presentation below is made under deterministic assumptions. For approaches motivated by stochastic models, see Aström (2012) and references therein.

Not all variables that appear in a model are of interest. The behaviors are usually captured by defining appropriate outputs. We choose outputs in order to describe those quantities that get focus. Food security can be considered as the principal outcome of food systems, if these systems are defined broadly and generically (Haddad, 2013; Allen et al., 2014; Burlingame and Dernini, 2011). 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 et al., 2010). Such drivers might also impact food security directly.

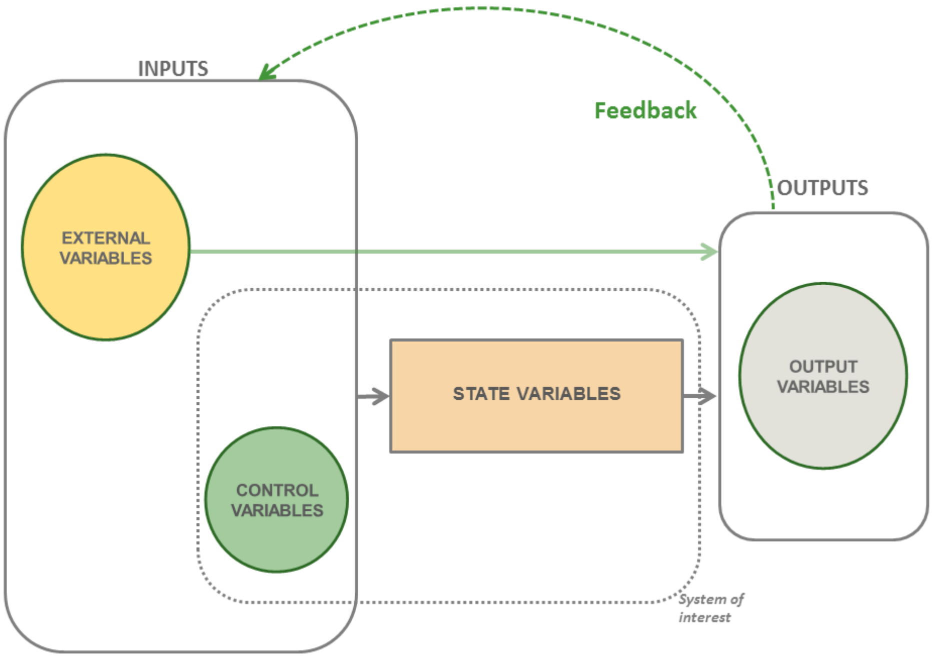

Figure 5 - Basic representation of a dynamic system (adapted from Rastoin and Ghersi, 2010)

The state of the system at a given time, is the extra piece of information needed, so that given the input trajectory, it is possible to determine the behavior of the system over time. We call x the state variables of the system. They provide the minimum amount of information that fully describe the system at any given time t. A mathematical description of the system in terms of a minimum set of variables x, together with knowledge of those variables at an initial time t_0 and the system inputs for time t, are deemed sufficient to predict the future system states and outputs for all time t.

Output functions are commonly used to characterize the input-output relationships. Dynamics of the system models are usually represented using differential or difference equations (with time as the independent variable). These equations, known as the transition functions, are formulated in state-space form that has a certain matrix structure.

The output equations are commonly written as[10]:

$$y_t = h(x_t, u_t, e_t) \qquad (4.1)$$

where h is a vector function with *n* components for the *n* outputs y of interest. All variables typically vary with time *t*.

Transition functions map the state of the model today into the state tomorrow. In vector notation, the set of differential equations may be written as:

$$\dot{x} = \frac{dx}{dt} = f(x_t, u_t, e_t) \qquad (4.2)$$

where *f* is any vector function. The system state at any instant *t* may be interpreted as a point in an *m*-dimensional state-space[11], and the dynamic state response x_t can be interpreted as a trajectory traced out in the state-space (Rowell, 2002).

Another two equations (4.3 and 4.4) can be added to the usual differential equation to map the feedback to inputs (Ionescu et al., 2009). The problem of parameter estimation pertains to the identification of data and determination of numerical values of the elements of these matrices.

$$\dot{e} = \frac{de}{dt} = g(x_t, u_t, e_t) \qquad (4.3)$$

$$\dot{u} = \frac{du}{dt} = \emptyset(x_t, e_t) \qquad (4.4)$$

Categorizing variables, constructing a composite indicator

[10] The notation below is a vector notation, which allows us to represent the system in a compact form.
[11] With *m* variables determining the state of the system.

As explained in the second section, we are looking for the essential variables describing a system and the variables we can act upon to redirect food system toward looked upon objectives. In the language of dynamic systems, we are looking for x and u, the state and control variables. These are the essential features of the system that determine the trajectory of the system and characterize sustainability. A system can be understood by the response pattern following a perturbation. Perturbation reveals the nature of the system. To capture something of the internal dialectic of system, we suggest fixing some crucial external variables, or drivers of changes e, and seeing how these affect one of the system outcomes, i.e. our outcome of interest: food and nutrition security.

To highlight the internal dialect of food systems, we suggest using the concepts from the already existing vulnerability/resilience framework to clarify what we would like to proxy; literally, vulnerability is the propensity or predisposition of a social-ecological system to be adversely affected by a change. Some global processes are significant drivers of change. There is high confidence that these include population growth, rapid and inappropriate urban development, international financial pressures, increases in socioeconomic inequalities, trends and failures in governance, etc. Vulnerability describes a set of conditions of people that derive from the historical and prevailing cultural, social, environmental, political, and economic contexts

As presented above, vulnerability/resilience is made up of three essential components: Exposure, sensitivity and resilience. Thus, vulnerability V can be regarded as a function of the components recovery potential (RP) and potential impacts (PI), which in turn are expressed by exposure (E) and sensitivity (S).

$$V = f(PI, RP), \qquad with\ PI = f(E, S) \qquad (3.5)$$

The vulnerability/resilience framework can first help structuring the different elements, i.e. categorizing variables with regards to others, and thus constructing a composite indicator in the absence of statistical application able to reveal the structure of the data, though procedures such as Principal Component Analysis (PCA). See (Prosperi et al., 2014) for a proposition of composite indicator. Second, the vulnerability/resilience framework allows articulating the different scales at which food systems are operating or embedded in. While defining system boundaries, attention should be paid to system level and spatial scale. The spatial scale at which the system is defined is crucial, as it will help identify the external variables affecting the system.

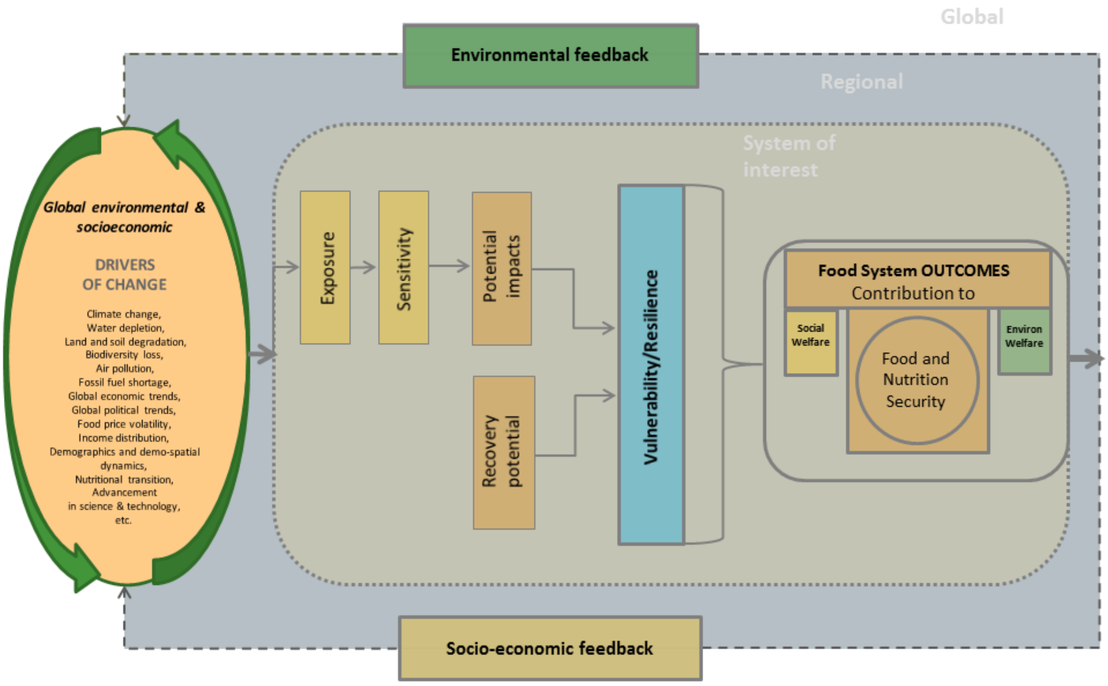

Figure 6 - A Sustainable food system framework (adapted from Turner et al., 2003; Ericksen, 2008; Ingram, 2011).

A map of the feedback structure of the system is a starting point. Building on the GECAFS food systems approach (Ericksen, 2008; Ingram, 2011), coupled with Turner et al.'s (2003) conceptualization of vulnerability, we suggest the framework represented in Figure 6 to model food systems' dynamics. Dynamic systems consider mainly two types of variables: endogenous and exogenous variables. Endogenous variables are the elements that are interactive within the boundaries of the system of interest. In the case at hand, these variables are defined at the national or sub-national level. On the contrary, exogenous variables are factors that are not enclosed by the system boundary but influence the system. Exogenous variables are on the other hand not directly influenced by variables enclosed within the system. Outcomes from the food system activities may however contribute to these external drivers, but geographically specified food systems are assumed *driver-takers*[12]. In our specific case, these external drivers of change are at the broader regional level or global scale. The three components of vulnerability – exposure, sensitivity and resilience – are the

[12] In the same way as consumers or producers are considered price-takers, in perfect competition, although price is collectively defined when overall demand and supply meet.

intrinsic features of the system that mediate the impact of the drivers of change on the food system's outcomes. These can be either state or control variables.

In this section, we specifically consider the large body of research on dynamic systems, and aim at applying this modelling approach to the assessment of food system sustainability. To assess the sustainability of the food system, we need to understand what might affect its processes, to which extent the drivers of change impact the food system's outcomes, and how actors respond to these pressures. Answering the question that was first posed by Carpenter et al. (2001) – "the resilience of what to what" or, in a similar vein, "vulnerability of what to what" – can provide useful guidance. These questions, in a step-wise approach, can activate the framework and model key issues related to food and nutrition security.

4.4 - Application: Addressing context-specific issues

A stepwise approach

Schroeter et al. (2005) developed an eight step methodological process to conduct vulnerability assessments. Following Schroeter et al. (2005), we propose a similarly structured and systematic method to apply the conceptual elements described in the above sections. These steps are preliminary to the identification of appropriate statistical variables, data application and scenario analysis. They involve proceeding in four stages:

1. Defining a study area and scale of analysis;
2. Identifying essential drivers of change;
3. Identifying essential food systems' outcomes;
4. Developing of a causal model by selecting essential interactions driver/outcome and examining respective systems' exposure, sensitivity and recovery potential.

Sustainability is usually conceived in place-specific terms. In the proposed framework, exposure to risks is dependent on the geographic context, and sensitivity and adaptive capacity are shaped by social and institutional factor elements (Eakin, 2010). The first step includes choosing a scale of analysis and drawing artificial boundaries around the coupled human-environment system of interest. Every system incorporates some sub-systems, which are themselves based on components, which are in fact sub-systems, etc. Two points are crucial to consider when defining the system level and spatial scale of analysis: i) who are the intended users of the measurement set and ii) what is the degree of granularity of the food system's outcomes to be address.

This work is part of the project "*Advancing through sustainable diets*" that has a focus on France and Spain. Given that the assessment is targeting policy-makers as main users, we opted for analysis at the population scale rather than the individual scale. It has thus been decided that the final level of analysis will be national or sub-national ("*Comunidad autónoma*" in Spain, "*Région*" in France and "*Regione*" in Italy). To draw the geographical boundaries, it has then been argued that the entities had to be subjected to similar type of food system concerns and exposed to similar type of drivers of change or factors of risk. Italy has thus been added to France and Spain as a possible study zone, on the ground that the three countries share similar food and nutrition security issues.

The northern coastal area of the western Mediterranean basin is commonly referred to as the "Latin Arc". It includes the coastal regions from Andalusia to Sicily. It is considered a homogeneous geographical entity closely related to certain summary representations of the European territory, at the regional level, proposed by geographers and urban scholars (Camagni and Capello, 2011; Barrio, 2004; Daviet, 1994; Voiron-Caniccio, 1994; Cortesi et al., 1996; Vanolo, 2007). It is also recognized as a consistent territory by institutions and local stakeholders for transregional policy and cooperation programmes (e.g. Western Mediterranean and Latin Alps, INTERREG II C Programme, EU; ESPON, 2010; Benoit and Comeau, 2005), sharing common cultural, institutional, socioeconomic and biogeographical determinants.

As mentioned previously, the spatial scale at which the system is defined drives the identification of the external variables likely to affect the system. Sub-global/regional is a natural level for studies of SES. The Mediterranean basin has been identified as one of the most prominent "hotspots" in future climate change projections (Giorgi, 2006), but also in terms of environmental unsustainability due to intense human activity and agricultural exploitation (Salvati, 2014). It has also been recognized as one of the first 25 Global Biodiversity hotspots in the world (Myers et al., 2000).

Identifying global and regional drivers of change affecting the food system outcomes

The second and third steps are crucial in applying the conceptual framework. It involves answering the question “vulnerability/resilience of what to what”. It requires identifying the main drivers of change simultaneously as the food system-specific issues of concern that the drivers are likely to affect (Schroeter et al., 2005). Several global and regional drivers of change affect the structure and processes of the food systems, putting at risk context-specific food and nutrition security outcomes. Based on an extensive literature review and discussions conducted over two focus groups gathering a group of seven experts, four critical food and nutrition security issues and four drivers of change have been identified at a sub-regional level. An exhaustive and rigorous literature review, specific for the Mediterranean region, highlighted existing urgent issues and crucial drivers of change (CIHEAM, 2012; SCAR, 2008; PARME, 2011). The selected four main drivers of change are the following:

Water depletion:

Water depletion is “a use or removal of water from a water basin that renders it unavailable for further use” (Molden, 1997). The Mediterranean region is greatly concerned by water stress and scarcity (FAO, 2011; PARME, 2011). The Western and Central Mediterranean areas are particularly subject to increasing water needs for domestic use, touristic and agricultural activities (Sousa et al., 2011). Water demand doubled in 50 years in Mediterranean countries (UNEP/Plan Bleu, 2006). The food system production and consumption patterns are increasingly water demanding. Irrigated agriculture only accounts for 70 % of the consumption of freshwater resources globally (OECD, 2013). In the EU-15, 85% of irrigated land is located in the Mediterranean area (France, Spain, Italy, Portugal, and Greece).

Water availability is closely related to climate change trends altering precipitation patterns and rainwater (Freibauer et al., 2011). Increase in the concentration of agrochemicals, soil nutrients, and a number of water pollutions are also observed, impacting the quality of water and further contributing to water scarcity (Bates et al., 2008).

Biodiversity loss:

Biodiversity[13] loss is defined as "the long-term or permanent qualitative or quantitative reduction in components of biodiversity and their potential to provide goods and services, to be measured at global, regional and national levels" (CBD, 2004). Biodiversity is globally at risk, with 20930 species and ecological communities known to be threatened (IUCN, 2013). The Mediterranean region has been in particular catalogued as one of the 25 biodiversity hotspots of the planet with an exceptional diversity of endemic species within ecosystems that are at great risk, with 19% of the species threatened for extinction (IUCN, 2008).

Biodiversity loss is cogenerated by climate change, environment depletion and water stress. It is strongly related to modern food production and consumption patterns (Altieri, 2000) that have become more intensive and homogenizing. The loss of agrobiodiversity is interlinked also with a number of causal factors, including habitat depletion, change in land use and management, GHG emissions, etc. (Tilman et al., 2002; Frison et al., 2011).

Food price volatility:

Food price volatility refers to large and atypical[14] "variations in agricultural prices over time" (FAO, 2011). Food prices increased sharply in 2008, with the FAO food price index breaking the threshold of 200[15] for the first time (SCAR, 2008). The Mediterranean region is a particularly vulnerable region with regards to price volatility, in particular due to its cereal dependence, nutrition transition, population growth, urbanization and climate change effects (Padilla et al., 2005).

Climate change impacts, changing trade patterns, new dietary trends and growing demand for biofuels are often invoked as among the causes of food price volatility. The rising demand for food and fuel, originated from consumption and industrial purposes, is engendered by both population growth and changes in food consumption patterns (Brown, 2008). Furthermore speculation on commodity markets and

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[13] Biodiversity is defined as the existence of species, genetic, and ecosystem diversity in an area (Swingland, 2000).

[14] See FAO report *Price Volatility in Food and Agricultural Markets: Policy Responses* (Annex A, 2011) for a more technical definitions of price volatility.

[15] Base 100: 1998-2000.

reduction of food stocks are also crucial determinants of price variations (Robles et al., 2009).

Changing food consumption patterns:

Changing food consumption[16] patterns refers to the changing structure of global food consumption, related to changing dominant values, attitude and behaviours (Kearney, 2010). Globally, food consumption patterns are changing both in terms of total amount and composition. Worldwide consumers have switched from considering animal protein a luxury food item to considering it a regular part of the diet (Meade et al., 2014).

Food choices are deeply embedded in social norms. Individual food consumption patterns – i.e. diets – are the results of changes in culture, social values and representations attached to food consumption, driving effectively behavioral changes and resulting in modified diets. The global changes in food consumption patterns – some talk about a "westernization" of food consumption patterns (Drewnowski and Popkin, 1997) – are largely driven by demographic factors and income growth, and related to changes in dominant values and lifestyle, influenced by globalization, urbanization, changes in occupational status and employment distribution, and more effective dissemination of information (Meade, 2012).

Identifying food and nutrition security issues

It is important at this point to formalize the hypotheses to be explored. The "what is vulnerable" is identified by the functions performed by the ecological and social service delivering entity composed of a number of actors, activities and processes. The system will be considered vulnerable if negative food system outcomes emerge. Food, or more precisely feeding population, is agriculture and food systems' main reason for being (Haddad, 2013). Human nutrition should be considered one of the most fundamental ecosystem services, or alternatively as dependent on several ecosystem services, including provisioning, regulating, supporting and cultural services (Deckelbaum et al., 2006).

[16] This social driver is proposed as one regime driver by the SCAR 2nd Foresight exercise report (2009), closely linked to the other social global driver "changing dominant values", and is exactly phrased "Consumption quantities and patterns", referring to literally to "food consumption patterns" and "nutritional transition".

Food security, defined as the situation that exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life (FAO, 1996), is a policy issue of importance in just about every country. It can be considered the principal outcome of food systems. It is also important to remember that food security is not just about the amount of food but also depends on the nutritional quality, safety and cultural appropriateness of foods (Liverman and Kapadia, 2010). Investigating the influence of socio-economic and environmental drivers on food and nutrition security, with regards to some essential food system characteristics, can provide an approach to think the causal mechanisms that can lead to unsustainability. As mentioned above, four food and nutrition security issues have been identified as crucial for the Latin Arc countries.

Nutritional quality of the food supply:

The Nutritional quality of food supply refers to the nutritional composition of the food products on the market (Oquali, INRA/ANES). The improvement of the nutritional quality of the food supply is one of the eight specific actions defined by the WHO European Action Plan for Food and Nutrition Policy 2007-2012[17]. A balanced diet is achieved through personal habits but also requires that the foods on offer to consumers have a satisfactory nutritional composition. In France, a food quality observatory (Oqali) was set up to monitor the quality of the food supply. Increasing availability and consumption of nutrient-poor and energy-dense foods and beverages lead to enhancement of human health problems, including obesity and non-communicable chronic disease.

Affordability of food:

According to Ingram (2011), affordability of food is “the purchasing power of households or communities relative to the price of food”. It refers to the “economic access” to food (Foran et al., 2014). Affordability is about food being available at

[17] The WHO European Action Plan for Food and Nutrition Policy 2007–2012 defines eight specific actions for “ensuring a safe, healthy and sustainable food supply: improve the availability and affordability of fruit and vegetables; promote the reformulation of mainstream food products; promote appropriate micronutrient fortification of staple food items and develop complementary foods with adequate micronutrient content; improve the nutritional quality of the food supply and food safety in public institutions; ensure that the commercial provision of food products is aligned with food-based dietary guidelines; explore the use of economic tools (taxes, subsidies); establish targeted programmes for the protection of vulnerable and low socioeconomic groups; establish intersectoral food safety systems with a farm-to-fork approach and in accordance with the Codex Alimentarius risk analysis framework.”

prices that people can afford to pay, and in particular, whether low-income consumers can afford to buy enough nutritious food to meet basic needs (Barling et al., 2010). The determinants of food affordability include pricing policies and mechanisms, seasonal and geographical variations in price, local prices relative to external prices, the form in which households are paid, income and wealth levels (Ingram, 2009). Food affordability and food prices are important determinants of food choices (Lee et al., 2013).

Dietary energy balance:

Dietary energy balance refers to the balance between caloric intake and energy expenditure (Patel et al., 2004). Excessive fat accumulation is acknowledged to be a risk factor for various health problems, including CVD, diabetes, cancers and osteoarthritis (WHO, 2014). Obesity has become a significant public health in high and medium income countries, with 500 million adults obese worldwide and more than 1 billion projected by 2030 if no major effort is made (Kelly et al., 2008; Finucane et al., 2011). Body weight results from the integrated effects of food consumption, physical activity and genetics. A range of environmental, social and behavioral factors interact to determine energy intake and expenditure, such as sedentary lifestyles, heavy marketing of both energy-dense foods and fast food outlets, adverse social and economic conditions, the consumption of high-sugar drinks, etc. (WHO, 2010; Swinburn et al., 2004).

Satisfaction of cultural food preferences:

Cultural food preferences are environmental factors related to social background, which contribute to food choices and intakes. It now acknowledged that honoring ethnic and cultural food preferences, compatible with nutritional requirements, is essential for food acceptance and wellbeing. Social and cultural norms have a crucial role in diet (Sobal et al., 1998). Food preferences, socially or culturally determined, are now recognized as a key consideration in food security, as highlighted already in the 1996 definition of food security. Assessing cultural issues surrounding food preferences may also help improve dietary adherence to recommendations.

A causal model

The fourth step is about developing a causal model, formalizing into a model the dynamics of exposure, sensitivity and resilience. The four drivers of change and four food security issues, presented above, are matched to explore their possible causal relationships. The proposed framework aimed at identifying the food system characteristics that make the food system capable of sustaining food and nutrition security outcomes. This can serve to identify warning signals, although the drivers and outcomes of interest will have to be evaluated as well. Results are presented in Table 2.

Table 2 - Interactions Drivers of change/FNS Issues

Drivers of change		*Food and Nutrition Security Issues*	References
		Nutritional quality of food supply	
WATER DEPLETION	Potential Impact	• Contributing to decrease of production and productivity of sufficient and nutritious foods. • Engendering low dilution capacity and consequent contamination of agrofood products. • Impacting the availability of quality foods for poor consumers through higher cost of water.	(Ericksen, 2010; PARME, 2010; Bates, 2008; SCAR, 2009; Brown, 2008; Wood et al., 2010; Johnston et al., 2010; Dangour et al., 2012)
	Recovery potential	• Fostering water productivity and efficiency to guarantee adequate nutritional values of foods. • Contrasting water scarcity through agrobiodiversity richness. • Enhancing adaptation through food import from water rich countries. • Reuse wastewater safely for use as water sources. • Focusing on human capacities and institutional framework.	(SCAR, 2011; Prosperi et al., 2014, Chapagain et al., 2006; Paul et al., 2010; UN-Water, 2014)
		Affordability of food	
	Potential Impact	• Altering productivity, prices and trade, and then food availability and affordability. • Increasing water prices lead to higher costs of agrofood production and to decrease in food affordability.!	(Wood et al., 2010; SCAR, 2011; Ingram & Kapadia, 2010)
	Recovery potential	• Encouraging drought-resistant crops utilization. • Fostering food import from water rich countries • Improving irrigation efficiency • Promoting waste water treatments	(Hellegers et al., 2008; Prosperi et al., 2014; Yang and Zehnder, 2008; Waughray, 2011;)

		Nutritional quality of food supply	
BIODIVERSITY LOSS	Potential Impact	• Shifting to ecologically simplified systems based on cereals contributes to poorly diversified diets. • Hampering food systems responses against climate change, with consequent impact on productivity. • Increasing the dependency on global varieties on external inputs.	(SCAR, 2011; Allen et al., 2014; Arimond et al., 2010; Roche et al., 2008; Randall et al., 1985; Torheim et al., 2000; Pelletier & Frongillo, 2003; Frison et al., 2006; Dangout et al., 2012; Johnston et al., 2014; Remans et al. 2011; Brunori et al., 2008)
	Recovery potential	• Promoting agrobiodiverse systems for ecosystem services, food security benefits (nutritional value of foods), the viability of agricultural systems and long-term productivity. • Fostering organic farming	(Thrupp, 2000; Reidsma and Ewert, 2008; Eakin, 2010)
		Satisfaction of cultural food preferences	
	Potential Impact	• Putting at risk cultural traditions and preferences, linked to regional varieties and diets. • Homogenizing food production. • Contributing to reduce the enormous amount of information, on nutritional and health benefits of the foods that shape the food cultural preferences of people. • Decreasing food biodiversity could result in the loss of unique and traditional foods.	(Liverman and Kapadia, 2010; Jacques & Jacques, 2012; Kuhnlein et al., 2009; (Kearney, 2010; SCAR, 2011).
	Recovery potential	• Knowing how to prepare a more varied diet can influence consumption of different food products. • Providing more varied and tasteful diets. • Enhancing and keeping traditional food cultures.	(Johnston et al., 2014; Khoury et al., 2014; Termote et al., 2010)

Drivers of change		*Food and Nutrition Security Issues*	References
		Nutritional quality of food supply	
FOOD PRICE VOLATILITY	Potential Impact	• Impacting food production and consumption. • Altering food supply towards disadvantaged groups. • Leading to profound changes in the composition and availability of food supplies. • Hampering the present agrofood system supply, strongly interlinked with fossil fuels system.	(WHO-EU site) (Friel and Lichacz, 2010). (DEFRA, 2008) (SCAR, 2009)
	Recovery potential	• Enhancing dietary diversity for avoiding dependency on few groups of foods. • Fostering local provisioning and production, less involved in price variations.	(Herforth, 2010; Pinstrup-Andersen, 2013)
		Affordability of food	
	Potential Impact	• Impacting household incomes and purchasing power. • Affecting agrofood productivity, and therefore food affordability and availability • Exacerbating economic shocks for the poor, who depend on wages and the rest of the economy. • Shifting purchasing strategies to lower quality products.	(Ingram, 2009; HLPE, 2011; SCAR 2011; Wood et al. 2010; Lee et al., 2013; UK Cabinet Office, 2008; SCAR, 2009; Regmi & Meade, 2014).
	Recovery potential	• Fostering food industry's focus on consumers and their need for "affordable food of high quality and diversity". • Shifting towards cheaper or locally available foods, meeting the same caloric and nutritional requirements. • Implement food policies for diversifying supply sources through different strategies (subsidies, food stamps). • Promoting diversity in food consumption patterns.	(Russo, 2008; European Technology Platform, 2008; Brunori and Guarino, 2010; Prosperi et al., 2014).

		Nutritional quality of food supply	
CHANGES IN FOOD CONSUMPTION PATTERNS	Potential Impact	• Influencing food industry production patterns, overall food security and nutritional characteristics of diets. • Shifting the demand towards cereals, simple sugars, animal products and highly processed foods.	(UNEP, 2012; Prosperi et al 2014; ETC, 2008; Brunori and Guarino, 2010; SCAR, 2011; WHO-EU site).
	Recovery potential	• Improving the understanding of the determinants of consumer choices. • Empowering consumers' choice for healthy and safe provided food. • Engendering consumption patterns cognizant of the impact of food choice on health.	(Allen et al., 2014; SCAR, 2011; Khoury et al., 2013).
		Dietary Energy Balance	
	Potential Impact	• Increasing consumption of fats, sugars, sweeteners, animal products, highly processed foods, and in fast foods and vending machines products. • Decreasing consumption in plant proteins and of home-prepared foods. • Strengthening "obesogenic" environments with little energy expenditure and sedentary lifestyles. • Altering frequency and the amounts consumed of foods. • Decreasing dietary diversity.	(PARME, 2011; SCAR, 2009; SCAR 2011; Johnston et al., 2014; UNEP, 2012; Popkin, 2002; Friel and Lichacz, 2010; Liverman and Kapadia, 2010; Ericksen et al., 2010; Nielsen and Popkin, 2004; Swinburn et al., 1999; UNSCN, 2000; Garrett and Ruel, 2005; Ley et al., 2006; Yatsunenko et al., 2012; Lozupone et al., 2012).
	Recovery potential	• Fostering public awareness for healthier diets through campaigns and community movements. • Enhancing cultural knowledge on preparing varied diets and on nutritional and health benefits of the foods. • Promoting weight loss and metabolic health through appropriate changes in the gut microbiota. • Supporting guidelines on dietary strategies to counteract overweight and obesity.	(Freeland-Graves & Nitzke, 2013; Termote et al., 2010; Kuhnlein et al., 2009; Obersteiner et al., 2010 2010; Barling et al, 2009; Lopez-Legarrea et al., 2014; Cardoso et al., 2013)

These sets of characteristics are indicating how changes in water, biodiversity, food prices and food consumption patterns are transmitted through the food system, including the sequencing of events and the scale of interactions; how the food system is sensitive to these changes; and the adaptive capacity of the food system. This could lead to subsequent work to identify thresholds of change and to model quantitatively the interactions among stressors, attributes, and outcomes, to improve the general understanding of food system sustainability. It more importantly offers the elements that need to be assessed, i.e. the attributes that indicators can be measuring.

4.5- Discussion

Why vulnerability and resilience to assess sustainability?

In this chapter, we propose to analyze and assess the sustainability of food systems using the concepts of vulnerability and resilience. First, vulnerability is not the simple flip side of resilience. Following Turner et al. (2003), we argue that articulating the two – overlapping – concepts provides a more comprehensive framework to capture the features of complex systems, such as food systems, perpetually evolving and re-organizing into unexpected new configurations. The identification of the elements within the system, and assessment of their sensitivity to change, in addition to the capacity of the system to cope, adapt and transform to these changes, are considered key to understanding dynamic systems. Resilience and vulnerability are relatively new, but now fundamental concepts in the contemporary language of sustainability sciences. The links between vulnerability and sustainability have been discussed against the backdrop of a long-standing dispute about the relations between sustainability and resilience. Resilience is commonly accepted as at least a crucial dimension of sustainability. Some argue that resilience of a system constitutes a necessary but not sufficient condition for sustainability (Derissen et al., 2011). How do the concepts of vulnerability and resilience square with the definition of sustainability?

Sustainability is a normative concept that provides abroad framework to guide actions. It requires defining specific goals – and their monitoring measures –that need to be agreed and acknowledged by all stakeholders (Anderies et al., 2013). The design of legitimate collective decision processes is crucial to sustainability. On the contrary, resilience and vulnerability as descriptive concepts characterize the dynamic properties of a system, and can thus help define these societal goals. Sustainability and vulnerability/resilience can thus be understood as distinct concepts operating at different levels, the latter concepts providing the elements to inform the decision process intrinsic to the formerconcept.

Although the concepts of "vulnerability" and "resilience" have entered the food policy discourse, the influence of SES thinking on policy-maker agendas has otherwise been rather limited (Foran et al., 2014). SES frameworks emphasize complexity and systemic interactions. Applications of these frameworks tend thus to focus on problem identification and improving system understanding (Nadasdy, 2007). As mentioned earlier, food systems are systems of variables connected to each other through causal pathways, which are further complexified by operating at different geographical or time scales. Vulnerability and resilience can be useful approaches to capture these relationships. One key conceptual element of vulnerability/resilience models is a clear distinction between causal events and outcomes (Dilley and Boudreau, 2001). It frames a "causal factor approach" that describes the interactions leading to the final outcomes. Exposure, sensitivity and resilience provide the concepts to identify the system's properties that shape causal pathways towards food system's outcomes.

Systems behave in a circular organization forming feedback loops. The proposed fragmentation in specific vulnerabilities and resilience factors – through the intersections of different drivers and issues – caninduce a certain degree of linearity in causality. Vulnerability and resilience answer questions about mechanisms that operate to produce outcomes under certain specific conditions. As such, it provides policy-makers with a model of highly formalized predictions of the effects of a limited set of variables (Epstein et al., 2013), which can be tested recursively and provide insights into possible feedback. Modelers are generally faced with the dilemma of how comprehensive a model to build: "one with many variables that ends up as a qualitative description, or one with a few key variables that acts quantitatively but lacks comprehensiveness" (Fraser et al., 2005). It has also to be recalled that sustainability as a forward-looking concept requires apprehending the conditions and determinants to maintain systems' functions over time. By focusing on a number of external forces and highlighting systemic internal dialectic, the vulnerability/resilience model allows a dynamic analysis of some specific issues of the food systems and provides direction for policy-makers.

Why these specific issues and drivers?

Building on Schroeter et al. (2005), two of the four sub-steps proposed to resolve the complexity that arise when integrating social and ecological approaches, imply specifying food systems' outcomes and external drivers. It requires first clarifying the principal outcomes or functions of a food system, in particular the issues at risk. Food systems serve several purposes and have several outcomes. What are the priority issues? Outcomes might be evaluated and ranked differently by different stakeholders, and at different levels. The proponents of the "Sustainable Diet" agenda highlight the food and nutrition security objectives of the food systems selected here as the end-point of the analysis (FAO/Bioversity, 2012). As mentioned above, following a review and after discussion in two focus groups, four food and nutrition security concerns have been retained judged crucial to the context at hand. However, other issues have been debated, such as "food safety" or "dietary quality". Other food systems' outcomes than food and nutrition security issues could also have been considered, such as environmental and socio-economic outcomes related to employment or equity. Food systems are responsible for diverse environmental, economic and social outcomes. Introducing these would have been maybe more in line with the general perception of what sustainability means. The articulation between food systems' defining elements and their resulting outcomes, the former contributing to predict the latter, could be expanded to other dimensions to further the modelling approach. Sustainability can hardly be modeled parsimoniously, raising then questions in terms of feasibility of the modeling.

The second step is to understand what and how global or regional changes, either socio-economic or environmental, might be transmitted through the activities to impact the outcomes, because food systems' complexity means that impacts may not always be felt directly. Experts invited to the focus groups mentioned other important drivers of change, such as "climate change" or "technological innovation". They also wondered if the model captures completely the internal drivers that are intrinsic to the system. Drivers are interacting with each other. Climate change and biodiversity loss are closely related for instance, with reciprocal influence. This interdependence raises some technical modeling concerns, named variables acting as possible proxy for other variables it is associated with. We thus aimed, as much as possible, to select priority drivers, excluding two drivers that are directly linked. Some analytical clarity and direction are indeed essential to convince policy-makers and have any policy impact. It is moreover desired to develop interventions that treat the underlying causes, rather than the symptoms of the unsustainability deriving from food systems. The concepts of vulnerability and resilience bring food security into consideration in a different way than in the past. Changes are happening and investigating the sources of adaptive capacity in the system is crucial. It also highlights that food security is a matter both for the North and for the South, although with different modes of expression, and cannot be dealt with only by looking at national concerns (SCAR, 2008).

4.6 – Conclusions

Developing policy to ensure sustainable food security is a tremendous challenge that requires a comprehensive and integrated analytical approach. Multiple factors influence the course of human-environment interactions, which are further complicated by the presence of co-evolving causal forces. Understanding these dynamics requires viewing the food system as a whole. Social-ecological system approaches allow moving away from looking at isolated events and their causes, and start to look at systems made up of interacting parts. Vulnerability and resilience is suggested in this chapter as a possible approach to capture the food system as a whole, think prospectively and identify the system elements that policy can leverage. The distinction in three components, namely exposure, sensitivity and resilience, provides the elements of a model that specify what attributes need to be measured and how to structure the different indicators in a coherent framework for improved decision-making and policies.

The concept of vulnerability and of resilience imposes a system thinking approach based on the interdependencies between drivers, system activities and properties, outcomes and feedback loops. Vulnerability and resilience of food systems can have multiple sources, and these sources may interact to generate unexpected responses (SCAR, 2008). As sustainability and food security becomes increasingly central, vulnerability/resilience will be among the principles that will drive the reformulation of research, as well as policies (Brunori and Guarino, 2010). Concepts and methods for global change, vulnerability/resilience assessments represent a new research frontier. More theoretical and empirical research is needed to measure and assess the interplay between human and environment systems, between causal factors and consequences. Appropriate tools have to be developed for monitoring,forecasting and integration in policy support measures.

Chapter 5

Using Delphi expert elicitation survey to define indicators for assessing the Sustainability of the Food Systems

5.1 - Introduction

The scientific and international debate on sustainability of diets and food systems is reaching strong popularity in research strategies and decision-making (FAO & Bioversity International, 2012). Interconnected environmental sustainability and food and nutrition security topics, and the debate about strengthening the links between food, health and environmental research are gaining increasing intensity (SCAR, 2011). However clear consensus on metrics of sustainable diets and food systems is still lacking and a host of efforts are being implemented towards this goal (Fanzo et al., 2012; Vinceti et al., 2013). Understanding what constitutes the assessment of the sustainability of food systems and diets is key for providing decision- and policy-making with knowledge of action, and having a systemic rationale and a framework to built a metric system is indispensible (Fanzo et al., 2014). It is necessary to investigate the impact of the determinants on the sustainability of diets and identify the appropriate tradeoffs related with recommendations and actions towards the sustainability of the food systems (Johnston et al., 2014).

The coexistence of undernutrition, nutrient deficiencies, overweight and obesity – the tripe burden of malnutrition – is inviting us to reconsider health and nutrition as the primary goal of food systems. Moreover, while improving food and nutrition security, agriculture and food industry have generated unintended consequences including environmental losses (UNEP, 2012; Allen et al., 2014). Simultaneously, several regions are experiencing unprecedented weather events caused by climate change and habitat depletion, in turn further destabilizing global food and nutrition security (Thompson & Cohen, 2012; Dora et al., 2014). This confluence of food crises with increasing environmental degradation suggests an urgent need for novel analyses and new paradigms to describe and understand the causes and facilitate adaptation and mitigation.

Participants at the 2010 international conference organized by the FAO and Bioversity International agreed on a common definition of sustainable Diets that emphasizes the food and nutrition security purpose of food systems, and the need to maintain or enhance this outcome over time – across generations – by preserving essential human assets and the flows of services they provide (FAO & BI, 2012). The concept of Sustainable Diets promotes economically, socially and environmentally sustainable food systems that concurrently ensure food and nutrition security (Fanzo et al., 2012; Johnston et al., 2014).

Modern societies depend on complex agro-ecological and trading systems to provide food. The move to sustainable diets calls for changes in the agricultural and food systems. Policy-makers and other stakeholders need evidence-based information and assessment tools to lead public policy interventions (Barrett, 2010). Sustainability in general provides decision makers with development strategies to allow present and future generations meeting their needs within the limits of the earth's capacity. Thus, it is a concept that offers a perspective of the dynamics that regulate the interconnection within social and ecological systems (Carpenter et al., 2009; Rockstrom et al., 2009; Waas et al., 2011). The sustainability of diets and food systems needs to be explored and assessed to provide decision-makers with information on socioeconomic and biophysical determinants and outcomes that regulate the system dynamics over time. However, in order to translate sustainability from a concept to a tangible strategy, indicators are key tools. Sustainability indicators can represent a set of metrics that measure characteristics or mechanisms that regulate the socio-ecological systems and ensure its continuity and functionality over time (Benitez-Capistros, 2014).

Metrics are an organized system combined to provide a perspective and have three principal objectives: inform civil society, industry, public officials and all stakeholders; measuring progress towards defined goals; aid decision making processes (UN, 2007). Indicators are variables that offer information on other variables that are limited (Gras et al., 1989). They synthetize the information (Andersen et al., 2013; Girardin et al., 1999; Mitchell et al., 1995; Rigby et al., 2001; Singh et al., 2012) and provide benchmarks for decision-making (Gras et al., 1989; Thivierge al.,2014). Indicators are variables that can simplify a complex message and are developed to transfer information to decision makers (Bell and Morse, 2008). Indicators of sustainable development at the national level are often identified through dynamic interactive and participatory approaches with stakeholders such as government representatives, technical experts, and civil society agents. Conceptual frameworks for indicators allow focusing and defining what to measure, what solutions and findings to gain from the assessment and what kinds of metrics to apply. Different frameworks have been developed for the assessment of sustainability because of different conceptual approaches and views, and different research goals.

However, the key differences among different frameworks reside in the interpretations of the dimensions of sustainable development, the interconnections between these dimensions, the structural organization and the concepts by which they justify the hypothesis for the selection and aggregation of the indicators (UN, 2007).

A sound theoretical framework is the starting point in constructing metrics (OECD, 2008). Sustainability – or Sustainable Development – is a necessarily complex concept that can have different understanding. In this exercise, we assume that a sustainability assessment aims at capturing the ability of a system to maintain and enhance its essential functions over time (Conway, 1985; Hansen, 1996). Sustainability addresses threats to preserving life support systems, including their capacity to withstand and adjust (Turner, 2010). It is then key to assess stocks of and changes in human and natural assets (Sen, Stiglitz and Fitoussi, 2009). Derived from a Sustainability sciences, the vulnerability approach, complemented by inputs from the resilience literature (Turner et al., 2003), is proposed to analyze the sustainability of critical food and nutrition security outcomes (Ericksen, 2008; Eakin, 2010; Prosperi et al., 2014). Vulnerability – as the degree to which a system is likely to experience harm due to exposure to a perturbation or stress – is a function of exposure, sensitivity, and resilience. Exposure is the nature and degree to which a system is likely to be affected by the occurrence of a change. Sensitivity is the degree to which a system is affected either adversely or beneficially, by a change. Resilience is the ability of a system to anticipate, absorb, accommodate, or recover from the effects of a potentially hazardous event in a timely and efficient manner, through ensuring the preservation, restoration, or improvement of its essential basic structures and functions (IPCC, 2012). Several global and regional drivers of change affect the structure and processes of the food systems (SCAR, 2009) putting at risk context-specific food and nutrition security outcomes (Ericksen, 2008). Based on an extensive literature review, four critical food and nutrition security issues and fours drivers of change have been identified. An indicator-based approach is then proposed to assess the sustainability of diets and food systems, through a vulnerability and resilience framework. These indicators can provide a detailed description of observable variables or interactions of variables relevant to the food and nutrition security. Indicators' selection is a crucial step and need to be realized beyond subjectivity and value judgments. Once that a framework defines the phenomenon to be measured, ideally the selection of the related individual indicators should be based on what is desirable to measure and not which indicators are available. Furthermore the transparency of the whole exercise is essential in constructing credible indicators (OECD, 2008).

Several decision support tools have been identified and applied for providing guidance to decision makers for solving problems in social-ecological systems and global change contexts, yet several approaches fail to be validated. Therefore it is usually recommended to use expert elicitation to offers solutions for decision-making (de França Doria et al., 2009). Hence, Delphi method represents a support tool for decision-making that implies the participation of a broad range of different experts, can be applied on a global scale, is based on anonymous responses, and can generate interactions between experts having different opinions and from different geographical backgrounds (Frewer et al., 2011). The Delphi method is a popular social research technique for forecasting and an aid in decision-making, and its aim is to obtain a reliable common opinion from a group of individual experts who can each make anonymous valuable contributions in order to resolve a complex problem on the basis of free opinions and knowledge and avoiding influences from personality and authority (Landeta, 2006; Linstone & Turoff, 1975).

Aims

The main goal of this research study is to identify a set of metrics of sustainable diets and food systems. The vulnerability and resilience framework was used as an analytical lens to provide a sequential list of sustainability indicators, while the Delphi method was used to determine which indicators are perceived as more relevant according to a selected group of participants. Delphi is an iterative questionnaire designed to elicit expert's knowledge. The study also investigated whether crucial information and further aspects related to food system sustainability were lacking in the structure proposed, which elements and interlinkages could be added and in which manner.

The system-oriented approach proposed - to the assessment of sustainable diets and food systems – incorporating elements from the vulnerability and resilience theories. The Turner et al.'s (2003) vulnerability/sustainability framework is one of the most quoted integrated conceptual models for vulnerability assessment (Gbetibouo et al., 2010). Exposure, sensitivity and resilience provide the concepts to identify the system's properties that shape a causal pathway towards food system's outcomes, and these are the variables that we aim to proxy through the Delphi expert elicitation process.

There is one crucial question the panel of experts were asked to answer: Vulnerability/resilience of what to what? Four main food and nutrition security issues – i.e. food system outcomes at risk specific to the Spanish, French and Italian context – and four global and regional drivers of change – relevant to the Mediterranean region and likely to impact the identified issues – were identified. Three questionnaires, over three iterative rounds, were used which included proposed indicators of exposure, sensitivity and resilience of four context-specific food and nutrition security issues, against fours drivers of change affecting the food system. Following the protocol of the Delphi Survey, participants were asked to discuss and complement the framework and underlying assumptions, and test the framework by selecting proxy indicators. Succeeding rounds were designed to bring the group to focus or consensus.

The second section of this chapter describes the Delphi approach adopted in this study, the participants, and the process undertaken. The third section describes the main findings of the study including consensus on indicators, drivers, issues, and on the vulnerability and resilience interactions proposed. The forth section reviews the usefulness and limitations of this study with respect to the results obtained and the methodology applied. We conclude that the Delphi-variant used in this study was useful in providing a clear and transparent means of exploring the complexities of the assessment of sustainable diets and food systems, and consensus was reached for a number of dimensions. Specifically, this study highlighted the challenges and the interest for further researches, through combining expert elicitation processes and a dynamic and analytical vulnerability and resilience framework, to generate a common working language and a set of metrics supporting decision-making for sustainable diets and food systems.

5.2 - Research design: Materials and methods

The Delphi technique is defined as "*a method of structuring a group communication process so that the process is effective in allowing a group of individuals as a whole* *to deal with a complex problem*" (Hugé et al., 2010). It is a procedure for organizing dispersed expert group debate to find answers to complex problems (Linstone and Turoff, 1975). Within several valuable expert elicitation tools, the Delphi approach proved helpful for involving experts in an iterative process of problem definition and analysis, in order to attain unbiased views and estimations on different complex issues (de França Doria et al., 2009) and convert these opinions into one or more communal notion/s through a feedback process (Benitez-Capistros et al., 2014). The Delphi technique is mostly applied by medical and engineering sciences, as well as in social sciences, and especially in different research domains and purposes spanning from medicine and public health (Hwang et al., 2006; Boulkedid et al., 2011), to agrofood systems policy and safety issues (Wentholt et al., 2009; Frewer et al., 2011), food security (Wolfe and Frongillo, 2001), development and selection of indicators of sustainability (Benitez-Capistros et al., 2014) of agri-environmental indicators to assess sustainability (Bélanger et al., 2012) and sustainable aquaculture (Fezzardi et al., 2013 - FAO), agro-based bioenergy (Rikkonen and Tapio, 2009), meat consumption (Vinnari and Tapio, 2009), educational research (Green, 2014), farm sustainability (Etxeberria et al., 2014), sustainability indicators for tourism (Choi and Sirakaya, 2006) and related weighting (Tsaur et al., 2006), environmental, scientific and policy evaluations and scenarios (Nowack et al., 2011; Swor and Canter, 2011; Wright, 2006), climate change impacts and vulnerabilities (Mastrandrea and Schneider, 2004; Webster et al., 2003; Arnell et al., 2005; Prato, 2008), adaptation to climate change and adaptive management (Plummer and Armitage, 2007; de Franca Doria et al., 2009), landscape and conservation management (Mehnen al., 2013), and vulnerability assessment (De Lange et al., 2010).

Generally a Delphi survey starts with an initial structured questionnaire - addressed to experts or participants - that leads to multiple interactions (rounds) between group members (expert panel) and the facilitator through a controlled feedback process. Once completed the questionnaires each expert is provided with a common feedback on the group responses. Often the facilitator indicates, individually to each participant, his/her position within the global feedback of the panel. Provided with this information, the participants complete the survey form again. Then he/she can confirm or amend his opinion on the basis of the information proposed - in the global feedback - by the other participants. Thus, in each round the participants are in some way asked to judge the opinions and elements that were suggested by the group on the preceding round. The process can be reiterated several times in as many different rounds until consensus emerges or is achieved. Usually consensus is reached following two to four rounds. However, a larger number of rounds often generates an important decline in the participation (Keeney et al., 2001).

Facilitators - in order to manage efficiently the Delphi study - have to consider that this iterative process can lead to large questionnaires with long lists of issues and information, that are time consuming to analyze, difficult to manage, and can further complicate consensus (Hasson et al., 2000; de França Doria et al., 2009; Benitez-Capistros et al., 2014).

Building blocks of any Delphi process are participants' anonymity (Landeta and Barrutia, 2011), a rigorous management of group through coalescing opinions and answering expert questions (Dalal et al., 2011), and letting participants the possibility to amend their opinions. In particular anonymity, together with large time frames between rounds, contribute to avoid bias problems typical of group dynamics and allow experts freely presenting their judgments on the topics (de França Doria et al., 2009).

In the present study, the Delphi method was conducted in an online environment, through emails sending and the web-based survey tool SurveyMonkey, an online survey creator (see www.surveymonkey.com). The online-based Delphi was adopted to improve the ergonomics of the process, avoiding unhandiness of paper-based surveys and easiness limitations as observed on other Delphi studies (Cam et al., 2002; Steyaert and Lisoir, 2005).

This Delphi study was conducted mainly focusing consensus around a list of indicators of sustainable diets and food systems over three iterative rounds. Experts were also asked with a number of open and appraisal questions with regards to the contents (drivers of change and issues of food and nutrition security) that compose the framework, in order to confirm or not the importance of the food system dynamics that were proposed to study, and to further open the analysis to other key aspects related to the sustainability of the food system. Before starting the Delphi process the framework, the indicators, the selection of participants, the survey, and the structure of the study were discussed in two exploratory focus groups (see figure 7).

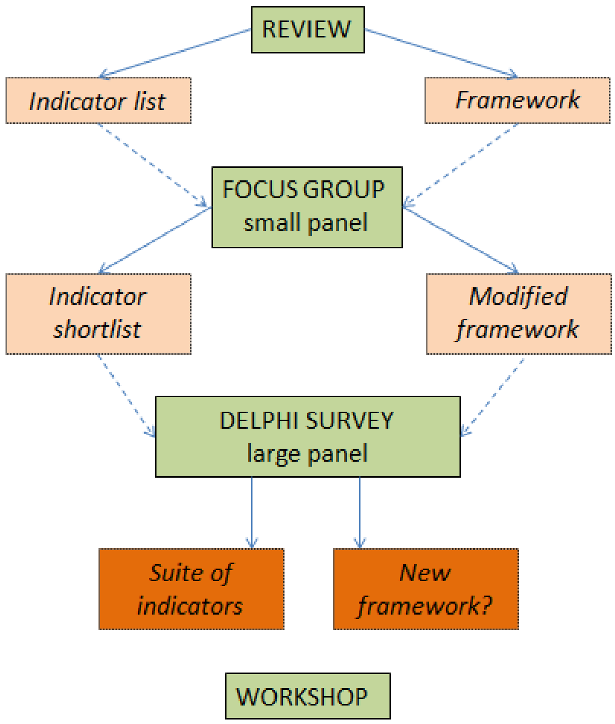

Figure 7 - Structure and pathway of the Delphi study

Participation and Panel composition

Selection of participants to a Delphi survey is critical. An expert is a person who is particularly competent as authority on a certain matter of facts (Flick, 2009). Identifying who is an expert - his/her expertise and knowledge - is challenging (Burgman et al., 2011; Failing et al., 2007), and selection must be performed thoroughly so that the group composition shapes the diversity of valuable knowledge (Okoli and Pawlowski, 2004; Steyaert and Lisoir, 2005). For the purpose of this research we considered an expert as a person who, by a verifiable mean (particular scientific role, expertise/knowledge, publications), is known to have information or has access to information with regards to the issues under investigation. In this study, we opted for a two-stage sampling procedure. In a first step, potential participants were selected by reviewing academic publications and participation to scientific conferences using broad keywords, and through professional networks. The sampling procedure identified experts working or doing scientific research on issues related to the sustainability of the food systems. Then we classified experts as a group of informed individuals, specialists in a field, or those with expertise about specific topics (see Keeney et al., 2001). The group included experts from a multiplicity of disciplines, to guarantee a heterogeneous array of opinions. 213 suitable candidates

were finally listed. Information on academic discipline, age and sex was collected. Potential participants were invited to participate by e-mail and then telephoned. Co-nomination was authorized when one of the experts declined (generally due to lack of availability) and suggested a colleague instead. In a second step, background variables (academic discipline, age and sex) were checked, and reminders and personalized emails were sent to individuals belonging to under-represented groups.
A first reminder was sent a week before the deadline for the first round and a second one four days later. On the last day, 41 questionnaires had been filled in. Therefore 18 experts were then contacted by telephone or, if not possible, sent another personalized email to balance the sample. An extra week was given to complete the questionnaire. At the end of this process 51 experts returned the questionnaire. For the second round two reminders were sent, and a few identified experts were further emailed to maintain a balanced panel. For the third round two reminders were also sent and a few experts were further emailed. The data were collected between March 2014 and July 2014.

Preparation and distribution of Delphi questionnaires

First, an electronic letter of invitation to the Delphi expert consultation was sent to the potential participants. The invitation (see Annex 1) enlightened the goals and methods of the study, and permitted potential participants to self estimate their expertise and aptness to the study (Dalkey et al., 1970). Two weeks later, a non-personalized email was sent to all identified experts with the link to the questionnaire and reading material. This material - distributed to all potential participants - comprehended a document explaining the conceptual background, the specific aim and purpose of the Delphi study (see Annex 2), and the indicator list (see Annex 3). Then, for each of the three consecutive rounds, electronic letters were sent to invite participants to fill in the questionnaire. The online questionnaire was first created in an MS Excel (XLS) environment and then directly uploaded to SurveyMonkey (see Annex 4). The obtained data was kept and could be downloaded in an XLS format for statistical and text analysis. Reports describing the results of each questionnaire were sent via email after each of the three Delphi rounds, separately to each participant. In the attached PDF file with the results, for each participant his/her individual choice was highlighted. The time frame asked to respond to each of the three consecutive rounds was of two weeks. However - as predicted - reminders were needed to send to let the maximum rate of participant respond. Extra time was necessary for some experts to fill in the questionnaires, therefore the actual time frame that participants were given has been of three weeks for the first round, and four weeks for the second and third rounds. After the first and the second rounds an additional time frame of eighteen days was required for completing the analysis of data and for providing participants with a modified questionnaire. Overall, the time elapsed between the delivery of the first questionnaire in round 1 and round 3 was approximately 3 months. The final results were given four months and ten days after sending the first letter of invitation to the Delphi expert consultation.

The Vulnerability and Resilience framework

This Delphi process is based on an integration of concepts and scientific approaches to study the broad topic of the sustainability of diets and food systems - including social-ecological systems frameworks, and theories and assessment of vulnerability and resilience - with the aim of identifying a set of metrics for improving decision-making. The vulnerability and resilience framework was applied building up the interactions between drivers of change and food and nutrition security issues - following the vulnerability framework proposed by Prosperi et al. (2014, pag. XX) - and disentangling these interactions in exposure, sensitivity and resilience. The vulnerability and resilience framework was chosen because of its proven suitability in the context of describing linkages between socioeconomic and biophysical causal factors within a given system, for its usefulness in multidisciplinary perspectives, and because it fills in science and policy gaps (Turner et al., 2003). Following the methodological guidelines of the vulnerability assessment (Schroeter et al. 2005) it has been possible to identify a geographical area of interest (the west Mediterranean Europe countries France, Italy and Spain), four drivers of change impacting the food system and four units of the food system likely to be vulnerable to changes (food and nutrition security issues); a set of interactions between these two categories (of drivers and issues) were identified. The drivers of change selected were adapted form the drivers proposed by the second report of the European Union's of the Standing Committee on Agricultural Research (2009) at the European level, such as water depletion, biodiversity loss, food price volatility, and changes in food consumption patterns . The vulnerable context-specific units of the food system were identified within the general food and nutrition security issues (availability, access, utilization) -

as main outcomes of a food system - following the main understanding brought by the definition of food and nutrition security (UN, 1996) and the framework of the food system in the context of global change (Ericksen, 2008; Ingram et al., 2010), such as nutritional quality of food supply, food affordability, dietary energy balance, and satisfaction of cultural food preferences . The interactions - between drivers and issues - were identified on the basis of the structure of the vulnerability framework (Prosperi et al., 2014), and related indicators were identified through an extensive and context-specific literature review (see Annexes 2 and 3).

Building on the mentioned vulnerability and resilience framework, the base structure for identifying the indicators was a matrix framework displaying the interactions between the "impacting" drivers of change and the "affected" food and nutrition security issues, within a complex interconnected food system (Allen and Prosperi, 2014 - Annex 2). The indicators were organized - for each vulnerability interaction - in the three components of vulnerability, such as: exposure, sensitivity, and resilience (Prosperi et al., 2014). The indicators were proposed for each of these three components following previous approaches to vulnerability assessment (Fussel and Klein, 2006; Schroeter et al., 2005).

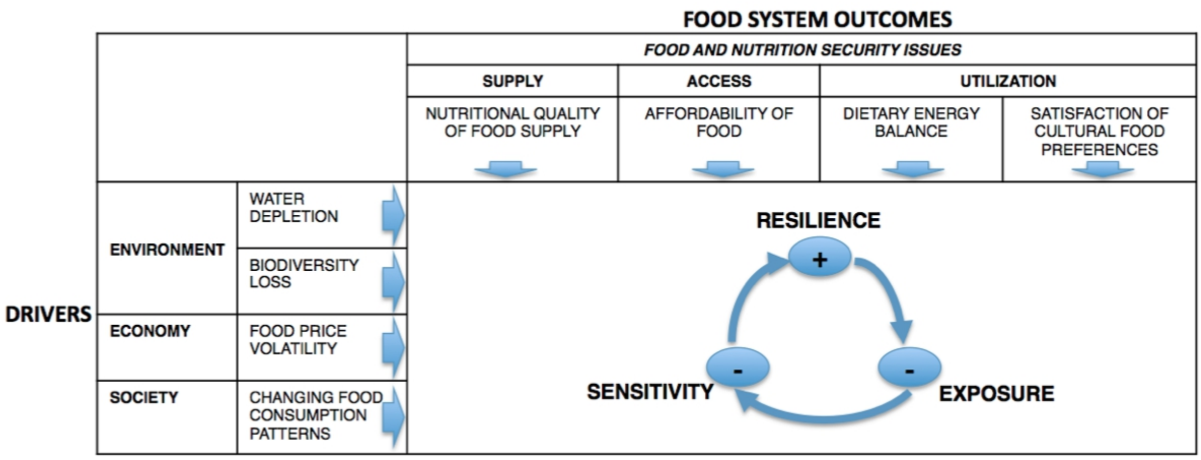

Figure 8 - Matrix of interactions between global, and regional, drivers of change and context-specific food and nutrition security issues (adapted from Prosperi et al., 2014)

Within a set of sixteen (4 drivers X 4 issues) (see figure 8) potential interactions of the matrix - between the drivers of change and the food and nutrition security issues mentioned above - only a selected subset of eight interactions were studied, analyzed, and then presented to the Delphi participants - accompanied by a detailed list of 136 indicators - for the selection of metrics (see Annex 3). These eight interactions involve the following potential impacts of the drivers of change on food and nutrition security issues and the related recovery potential from the food system unit concerned:

1. Impact of Water Depletion on the Nutritional Quality of Food Supply [WD/NQFS]
2. Impact of Water Depletion on the Affordability of Food [WD/AF]
3. Impact of Biodiversity Loss on the Nutritional Quality of Food Supply [BL/NQFS]
4. Impact of Biodiversity Loss on Satisfaction of cultural food Preferences [BL/SCFP]
5. Impact of Food Price Volatility on Nutritional Quality of Food Supply [FPV/NQFS]
6. Impact of Food Price Volatility on the Affordability of Food [FPV/AF]
7. Impact of the Changes in Food Consumption Patterns on the Nutritional Quality of Food Supply [CFCP / NQFS]
8. Impact of the Changes in Food Consumption Patterns on the Dietary Energy Balance [CFCP/DEB]

Following the protocol of the Delphi Survey, participants were asked to discuss and complement the framework and underlying assumptions, and test the framework by selecting proxy indicators. The questionnaires were composed of three sections: the selection of indicators; the appraisal and the proposition of drivers and issues; the open-ended questions. Three questionnaires, over three rounds, were used which included proposed indicators of exposure, sensitivity and resilience of four context-specific food and nutrition security issues, against fours drivers of change affecting the food system. Succeeding rounds were designed to bring the group to focus or consensus.

As mentioned above, the suggested framework and the initial shortlist of indicators were developed in discussions with selected expert focus groups. In fact it is strongly recommended - for Delphi process - to gather an exploratory workshop to refine round one Delphi. The objective is ensuring the best, most comprehensive, and most focused issues for involving participation in a quantitative survey and overcoming possible limitations of international participation. Furthermore, the experts participating in the focus groups can facilitate the implication of researchers or other experts within their contacts, for participating in the Delphi process (cascade methodology) (Fewer et al., 2011). Six experts participated in the focus groups, as senior researchers from multiple disciplinary backgrounds closely related to the sustainability of the food system, including also a specialist of the Delphi method. The meetings with the reduced panel in the focus groups consisted of a presentation of the proposed framework and discussion on it and on the main issues and drivers considered, and on the criteria for reducing the pools of indicators. The goals of these focus groups were to test the questionnaire and to anticipate the perception of the large panel of experts. The focus groups meant also to represent a sample for exploring the practical applications in the large survey panel of experts. In the present study, the selection criteria (related to keywords for drivers of change and issues, and to the mechanisms of the food system functioning) were explained to the experts in the focus groups. The exploratory focus groups allowed improve the ergonomics of the online survey, reduce and ameliorate the list of indicators provided, enlarge the contacts of potential participants to invite, and verify that policy issues under discussion were particularly relevant.

Data analysis

In each round participants were asked to select the best indicator within each of the 24 components presented. Indicators that not received any participant preference were excluded from the framework. New indicators were added if at least two participants proposed the same - or similar - proxy variables to enter in a specific component (only indicators proposed by at least 2 participants were reported - Indicators were considered as close enough when at least 2 words in the title or details of the indicators were common or judged similar [eg. “Number of crops”, “variety of crops” and “crop concentration”]). The questionnaire implied also questions on the appraisal of the framework, other than the selection of the indicators. Thus, participants were asked to judge the importance of the drivers of change and the proposed interactions, and to rank through a Likert scale the issues of food and nutrition security. It was also asked - not compulsorily - to propose further drivers and issues.

The data analysis of each round was based on descriptive statistics that were returned to experts through an iterative process. For the selection of indicators - in the three rounds - the results were indicated in percentages. For the close-ended questions -

such as, Not at all important / Not that important / Important / Very Important - on the appraisal of drivers and interactions, the results were indicated in percentages of rating. With regards to the appraisal of the food and nutrition security issues, a Likert scale was used for the evaluation of a 9-point (with 1 being the lowest and 9 being the highest). Except for the indicator selection, the appraisal of the elements of the framework was conducted through single assessments that were not reiterated in the Delphi process. In the argumentative section, qualitative comments were categorized and reported in each feedback. Higher priority was placed in addressing comments raised by a higher proportion of experts, and in those that were associated with higher disagreements. The purpose of this procedure was to minimize biases attributable to the facilitator during the process.

5.3 - Results

The Delphi sample characteristics

Usually Delphi studies involve on average between 15 and 60 experts, and within this range a Delphi panel is generally considered valid (Hasson et al., 2000). In this Delphi study 51 experts, corresponding to 24% of the all experts that were invited, returned the questionnaire of the first round. However this actually indicates a response rate of 72% of those who acknowledged receiving the invitation (see Table 3). Comparable decreases of participation were observed in other Delphi studies (Frewer et al., 2011; Wentholt et al., 2009). Nonetheless, in other cases, the number of experts is not always considered key. It is rather required a balanced composition of the panel and an adequate quality level of participants (Powell, 2003). Strong variations of the panel through the Delphi process or disequilibria might lead to recommend stopping the study earlier than expected (Benitez-Capistros et al., 2014).

With regards to the experts who replied to the first round questionnaire, 66% were males and 34% were females. The majority (33%) are economists – although from different sub-disciplines ranging from agricultural and food economics to resources and environmental economics – closely followed by nutritionists (22%). Agronomists and environmental scientists represent 10% and 8% respectively, and food technologists 4%. About 12% of the panel can be associated to sustainability science(s) and another 8% as working specifically on food policy and governance. We focused on agrofood economists and nutritionists, as they are the main groups who have published in the area of sustainable diets and food systems. Women represent about one third of the sample (31%). Economists and nutritionists remain within limits (36% and 28% respectively). System agronomists and sustainability scientists represent 10% each, and ecologists and food policy/governance specialists 8%. Only 1 panelist brings in food technology expertise.

In the round two - given the relatively small samples in Delphi surveys - achieving and maintaining a certain degree of participation was crucial to ensure the validity of the study. Overall, 39 experts (out of 51) logged in again and answered to the second round of the questionnaire, i.e. a response rate of 76.5%, above the highest threshold (70%) encountered in the literature (Akins et al., 2005). Two reminders were sent, and a few identified experts were further emailed to maintain a balanced panel. Women represent about one third of the sample (31%). Economists and nutritionists remain within limits (36% and 28% respectively). System agronomists and sustainability scientists represent 10% each, and ecologists and food policy/governance specialists 8%. Only 1 panelist brings in food technology expertise.

In the round three - 36 experts (out of 39 of the second round) responded to this third and last round of the survey, i.e. a response rate of 92%. As for previous rounds, two reminders were sent and a few experts were further emailed to maintain a balanced panel. Final participation indicates that women represent about one third of the sample (31%). Economists and nutritionists are still the best represented (33% and 22% respectively). A few nutritionists joined the group of those presenting themselves as food security or food policy experts (14%). Agronomists and ecologists represent about 8.5% of the panel each, and declared sustainability scientists 5.5%. Participants suggested two new groups: statisticians (5.5%) and food system specialists (3%). One panelist brings in explicitly food technology expertise. Confirmation about the scientific field of the experts was asked just in the last round, to avoid overload the previous rounds. Still the answers confirmed the heterogeneity level of the panel over the Delphi process that was maintained through constant monitoring of the multidisciplinary composition (see Table 4).

Table 3 - Global response and participation rates

	INVITATIONS SENT	NOT AVAILABLE	AVAILABLE (IN THEORY)	CONFIRMED RECEIVED	ROUND 1	ROUND 2	ROUND 3
Response rate	213	25 *(11%)*	188	71 *(38%)*	51 *(72%)*	39 *(76%)*	36 *(92%)*

Table 4 - Participation rate by composition of the panel (from invitation to the final round)

DISCIPLINE	INVITATIONS SENT		ROUND 1		ROUND 2		ROUND 3	
Economics	48	*23%*	17	*33%*	12	*31%*	11	*31%*
Nutrition	35	*16%*	11	*22%*	9	*23%*	8	*22%*
Ecology/Environmental resources	34	*16%*	4	*8%*	3	*8%*	3	*8%*
Agronomy	27	*13%*	5	*10%*	3	*8%*	3	*8%*
Food sec/policy	26	*12%*	6	*12%*	5	*13%*	5	*14%*
Food systems	15	*7%*	3	*6%*	2	*5%*	1	*3%*
Sustainability	14	*7%*	2	*4%*	2	*5%*	2	*6%*
Food tech	9	*4%*	1	*2%*	1	*3%*	1	*3%*
Statistics	5	*2%*	2	*4%*	2	*5%*	2	*6%*
Global / Response rate	213	-	51	-	39	*76%*	36	*92%*

Progression of consensus on the indicators

Delphi round 1

In this initial step of the survey it is common to observe largely distributed inputs for indicator preferences. Majority is reached just for 4 indicators and dimensions, while in 12 dimensions we observe one or more indicators reaching 35% and in 8 dimensions all indicators are still below 35%. 4 initial indicators were not selected by and were then excluded from the list for the round 2. On the other hand 14 new indicators were proposed by participants and introduced for selection in round 2. A descriptive analysis of the results of this stage is still not appropriate for indicators.

Delphi round 2

Consensus is clearly emerging for 10 of the 24 desired indicators (i.e. more than 60% agreement on one indicator); however no indicator has yet met the defined high threshold consensus criteria (80%). For some interactions and components, panelists seem to be balancing between two main options (7 out of 24 with two indicators displaying more than 30% agreement each). 31 indicators proposed in the round 2 were not selected and were then excluded from the list for the round 3. Experts suggested 4 new indicators that were integrated to the questionnaire for selection in round 3.

Delphi round 3: final results

Consensus is finally reached for 14 of the 24 desired indicators: 8 indicators have met the high threshold consensus criteria (80%), 3 the medium threshold consensus criteria (70%) and another 3 the low threshold consensus criteria (60%). Another 4 indicators have been selected by the majority of the participants (above 50%). These values that define the different rates of consensus criteria were proposed by Keeney et al. (2010) and are largely acknowledged in Delphi studies. Furthermore, according to Hasson et al. (2000) and de Franca Doria et al. (2009), it is also suggested that consensus between 51% and 80% should be considered acceptable.

For 5 dimensions (out of 24), clear bipolarity can be reported (two indicators above 35%). In some of these cases, several experts have recommended constructing a composite indicator. 3 dimensions remain unresolved with a wide dispersion of expert opinions among indicators and little improvement of the consensus through the rounds. Furthermore, "Don't know" rates (the default option) are high only for these 3 dimensions. 23 proposed indicators were not selected in this round by any of the participants. Globally 56 (4 + 31 + 24) indicators were - in the first, second and third rounds - completely rejected by the panel by a rate of respectively 3%, 21% and 20% over the total indicators proposed in each round.

On average, 93% of the experts who selected the favorite indicator per dimension (at least 50%) in the second round confirmed their choices in the third round. Although there is no specific statistical test to measure the stability of responses between rounds for qualitative nominal variables, this observation indicates that a certain degree of stability of the consensus has been achieved.

Furthermore, 75% (18 out of 24) of dimensions reached, at least, a majority consensus (≥50%) on one indicator, and in all these cases the indicator which was the most chosen in the round 3, was been also the most chosen in the round 1 and in the round 2 (see Table 5). This additional observation contributes also to demonstrate a certain degree of stability of consensus. The progression of consensus is thus ascending over the three rounds (see Figure 9).

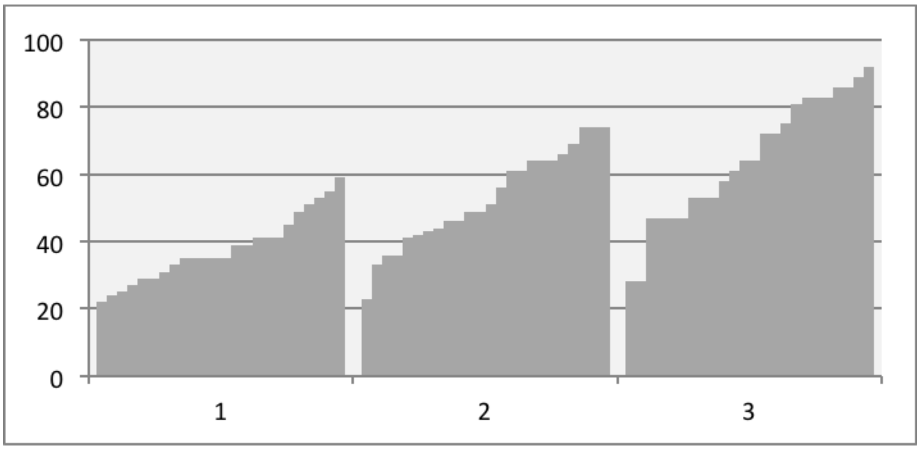

Figure 9 - Share of consensus (expressed in %) of the most selected indicator for each of the 24 vulnerability components considered (exposure, sensitivity, resilience) within each interaction over the three rounds (in ascending order of consensus)

Table 5 - Consensus rate (%) of the most selected indicator/s per vulnerability component in the three Delphi rounds

	ROUND 1		ROUND 2		ROUND 3	
	NUTRITIONAL QUALITY OF FOOD SUPPLY / WATER DEPLETION					
EXPOSURE	Water Footprint of nutrient-dense foods	*35*	Water Footprint of nutrient-dense foods [m3/kg]	*56*	Water Footprint of nutrient-dense foods [m3/kg]	*75*
SENSITIVITY	Intensity of use of actual water resources	*35*	Intensity of use of actual water resources	*49*	Intensity of use of actual water resources	*61*
RESILIENCE	Irrigation Water Efficiency Index	*51*	Irrigation Water Efficiency Index	*64*	Irrigation Water Efficiency Index	*83*
	AFFORDABILITY OF FOOD / WATER DEPLETION					
EXPOSURE	Water Footprint for an average diet	*39*	Water Footprint for an average diet	*67*	Water Footprint for an average diet	*86*
SENSITIVITY	Price index for 10 most water-demanding foods *AND* Price elasticity of demand for 1 most water-demanding foods	*27*	Price index for 10 most water-demanding foods	*51*	Price index for 10 most water-demanding foods	*53*
RESILIENCE	% of farmers who grow drought-resistant crops	*25*	Cross-price elasticity of demand of high/low water demanding foods	*36*	Cross-price elasticity of demand of high/low water demanding foods	*47*
	NUTRITIONAL QUALITY OF FOOD SUPPLY / BIODIVERSITY LOSS					
EXPOSURE	% of total acreage of top 5 varieties	*41*	% of total acreage of top 5 varieties	*44*	% of total acreage of top 5 varieties	*64*
SENSITIVITY	Nutritional Functional Diversity	*41*	Nutritional Functional Diversity	*69*	Nutritional Functional Diversity	*83*
RESILIENCE	Crop Agrobiodiversity Factor	*53*	Crop Agrobiodiversity Factor	*74*	Crop Agrobiodiversity Factor	*89*
	SATISFACTION OF CULTURAL FOOD PREFERENCES / BIODIVERSITY LOSS					
EXPOSURE	Time available for food preparation	*24*	Import Dependency Ratio	*33*	Import Dependency Ratio	*47*
SENSITIVITY	% of diets locally produced	*49*	% of diets locally produced	*62*	% of diets locally produced	*72*
RESILIENCE	Integration of biodiversity considerations in business	*29*	Integration of biodiversity considerations in business	*49*	Integration of biodiversity considerations in business	*53*
	AFFORDABILITY OF FOOD / PRICE VOLATILITY					
EXPOSURE	% of food household expenditure	*39*	% of food household expenditure	*62*	% of food household expenditure	*81*
SENSITIVITY	Sensitivity to price volatility	*55*	Sensitivity to price volatility	*74*	Sensitivity to price volatility	*86*
RESILIENCE	Presence of food safety net programs	*45*	Presence of safety net programs	*46*	Presence of safety net programs	*53*
	NUTRITIONAL QUALITY OF FOOD SUPPLY / PRICE VOLATILITY					
EXPOSURE	% of nutrient intakes from 10 most volatile foods	*35*	% of nutrient intakes from 10 most volatile foods	*64*	% of nutrient intakes from 10 most volatile foods	*72*
SENSITIVITY	Price elasticity of 10 most nutrient-dense foods	*31*	Price elasticity of 10 most nutrient-dense foods	*44*	Price elasticity of 10 most nutrient-dense foods	*47*
RESILIENCE	Household Dietary Diversity Score	*59*	Household Dietary Diversity Score	*74*	Household Dietary Diversity Score	*92*
	NUTRITIONAL QUALITY OF FOOD SUPPLY / CHANGE IN FOOD CONSUMPTION PATTERNS					
EXPOSURE	Food Purchasing Power Index	*35*	Food Purchasing Power Index	*46*	Food Purchasing Power Index	*64*
SENSITIVITY	Household Dietary Diversity Score	*35*	Household Dietary Diversity Score	*64*	Household Dietary Diversity Score	*83*
RESILIENCE	Existence of national dietary guidelines	*22*	% of public expenditure on food subsidies	*23*	% of public expenditure on food subsidies *AND* Existence of national dietary guidelines	*28*
	DIETARY ENERGY BALANCE / CHANGE IN FOOD CONSUMPTION PATTERNS					
EXPOSURE	At-risk-of-poverty rate	*41*	At-risk-of-poverty rate	*46*	Caloric share of ready-to-consume products	*47*
SENSITIVITY	Prevalence of overweight & obesity	*33*	Prevalence of overweight & obesity	*41*	Prevalence of overweight & obesity	*58*
RESILIENCE	Literacy rate of adults	*29*	Existence of policy plan for overweight/obesity	*36*	Existence of policy plan for overweight/obesity *AND* Funding allocated to nutrition education	*28*

Appraisal of Interactions, Drivers, and Issues

Drivers

Four drivers of change were included in the initial framework, such as Water Depletion, Biodiversity Loss, Food Price Volatility and Changes in Food Consumption Patterns. In the first round experts were asked to propose other drivers likely to affect each of the suggested food and nutrition security issues. 65% of the panel made 139 propositions. 25% of them proposed drivers that already emanate from the framework and 75% were original suggestions. Each driver was classified according to the 2nd EU-SCAR Foresight Exercise's typology of drivers likely to significantly impact food systems' prospects (SCAR, 2008).

We were able to associate most of the participants' propositions with a shortlist of 12 broad drivers of change: Agrifood patterns (including industry and market structure) (25%); Policies (including Agri/Energy/Rural/Trade/Food policies) (25%); Technological innovation (including Genetics/Machinery/Breeding/Food technology/Nanotechnology) (11%); World population (including Migration flows) (9%); Soil degradation (7%); Global economy trends (including Income distribution) (6%); Climate change (5%); Energy prices (4%).

As regards additional potential drivers affecting the nutritional quality of food supply, participants highlighted the importance of considering potential impacts from Technological innovation and Soil degradation (24% and 17% respectively). Climate change, Policies and Agrifood patterns (i.e. agrofood industry and market structure) are the second most quoted drivers, with around 10% of the proposals.

As regards additional potential drivers affecting affordability of food, two main drivers were suggested: Policies (30%) and Agrifood patterns (24%). Energy prices and Global economy trends were proposed by 11% and 8% respectively of respondents.

As regards additional potential drivers affecting dietary energy balance, Policies stands out as a main driver to consider (43%). World population (29%) and Agrifood patterns (14%) would come second. Changing dominant values and diversity in lifestyles – included in the global Changing food consumption patterns driver – have been frequently repeated.

As regards additional potential drivers affecting the satisfaction of cultural food preferences, Policies (36%), Agrifood patterns (27%) and World population (18%) are the most added drivers.

In order to prepare the questionnaire for the second round, the proposed drivers were added to the initial set.

Interactions

In the second round experts were asked to rank the importance of the eight initial interactions (between a driver of change and a food and nutrition security issue). All the eight proposed interactions have been judged "important" or "very important" by more than 80% of the panelists. Agreement on importance ranges from 85% (impact of biodiversity loss on nutritional quality of food supply) to 97% (impact of changing food consumption patterns on dietary energy balance) (Figure 10).

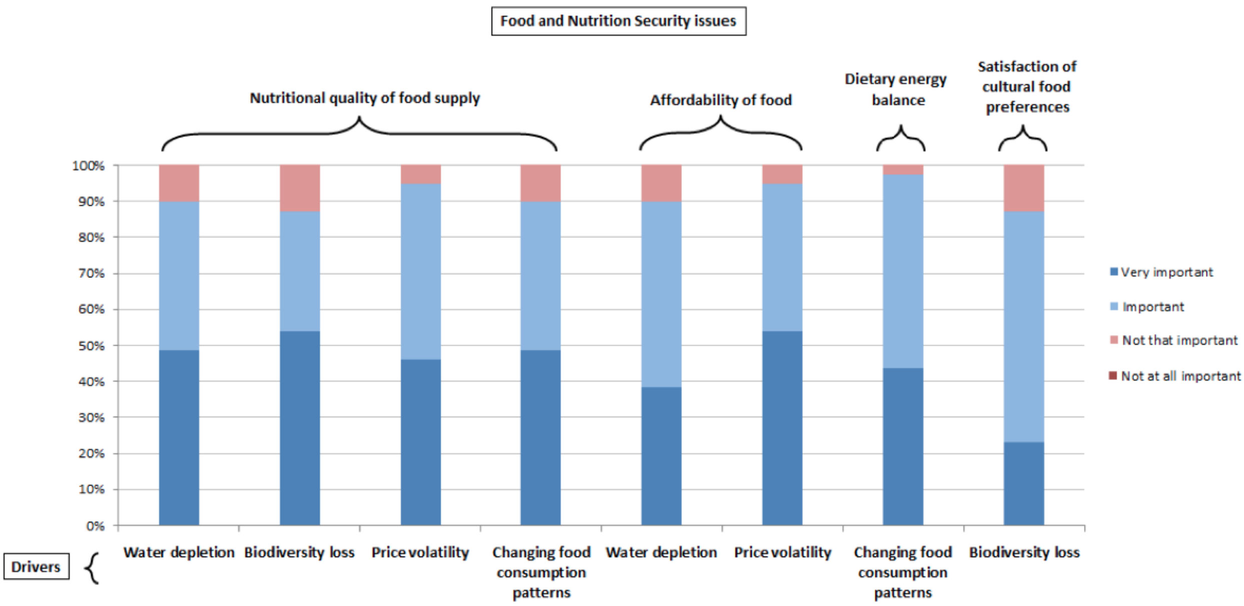

Figure 10 - Expert appraisal of the eight interactions proposed in the Delphi study for the selection of the indicators

In the second round, the two first proposed drivers, per issue, were submitted to the participants for ranking according to importance.

Overall, the newly proposed drivers have not reached the same high degree of consensus on importance for food and nutrition security as the initial set. Mainly three have attained comparable levels for some issues (near or above 80%), namely: Changing agrofood patterns, Policy actions and Technological innovations (See figure 11). In particular, population dynamics appear not to be considered a priority concern for food and nutrition security.

It has to be reported that Climate change, proposed by 5% of the respondents in the first round, has been highlighted again in the open ended questions as an important driver to consider per se, in addition to Water depletion and Biodiversity loss.

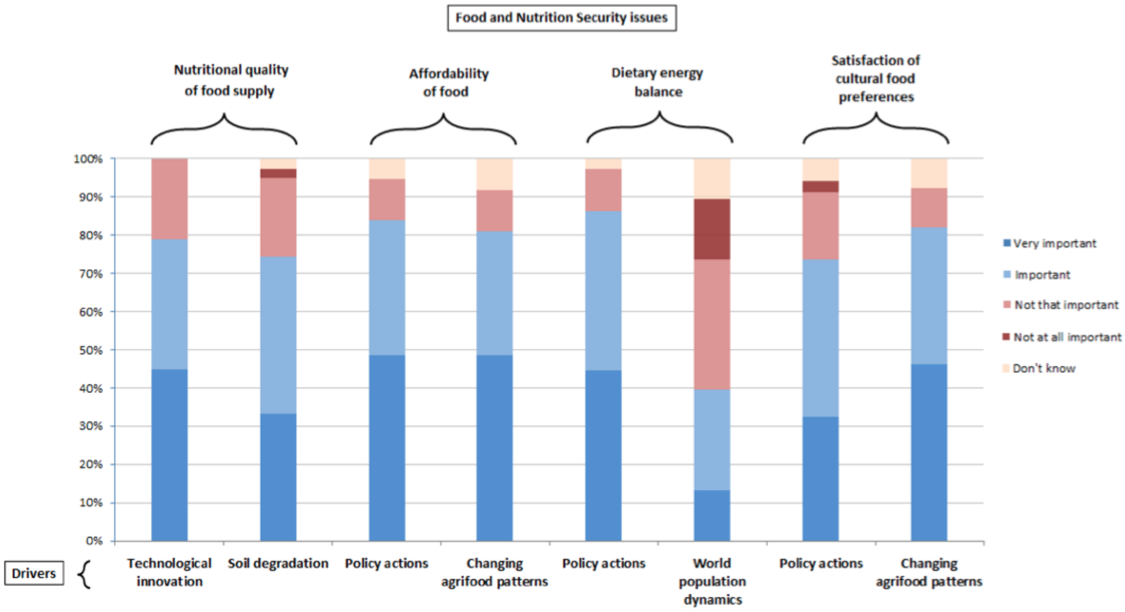

Figure 11 - Expert appraisal of the emerged interactions between the initial set of food and nutrition security issues and the newly proposed drivers of change

Food and nutrition security issues

In the second round participants were invited to propose new food and nutrition security issues judged important for the geographical context considered (Spain, France and Italy), in addition to the four Food & Nutrition Security context-specific issues proposed in the framework. 18 experts (45%) answered to this non-compulsory question and respondents suggested 5 additional issues. Two of these are not generally considered as conventional food and nutrition security issues, as usually encountered in the literature (Pangaribowo et al., 2013). Discussions should now focus on whether these two issues would actually fall within the sustainable food and nutrition security realm.

Accessibility has been suggested as another food and nutrition security issue by 3 participants, "next to affordability". An expert specified that "physical access" was a particular concern to consider. Another stated that "allocation of food within society/household" is an issue when discussing accessibility. Food safety was another issue mentioned. One expert mentioned "food system sovereignty and governance (transparency in decision-making, ability of consumers and producers to influence food system drivers and outcomes)". Other panelists talked about "food production patterns" and "re-orientation of industry [organization] or technological improvement" along the value chains. Several experts added "environmental impacts" or "externalities". Others specifically mentioned "greenhouse gas emissions" or "biodiversity" or "water use" or "energy consumption", as food and nutrition security issues. An expert highlighted the importance of "increased inequality in wealth/income distribution", while others added "inequitable (and unethical) healthy food distribution" or "equity" as food system outcomes that need to be considered. Another expert mentioned labor regulations and corporate social responsibility as crucial elements for the future of the food systems.

The propositions of the experts have then been analyzed and categorized in five additional issues, namely: (Physical) accessibility, food safety, governance, environmental externalities and equity.

Participants were then asked to rate the priority of these nine issues using a scale of 1 to 9 (with 1 being the lowest and 9 being the highest) (see figure 12). The four initial issues appear within the first five priority challenges for food and nutrition security identified in the region. "Nutritional quality (of food supply)" is ranked the most important current issue (5.8). Two new challenges – "Environmental" externalities" and "social equity" – come second and third (5.6 and 5.3 respectively). As already highlighted, these two crucial questions are not conventional food and nutrition security issues, as usually encountered in the literature (Pangaribowo et al., 2013). "Satisfaction of cultural food preferences" (5.2) is judged the fourth most important issue, closely followed by "affordability of food" and "dietary energy balance" ex-aequo (5). The other three proposed issues fall below the median value of the scale"–"i.e."5."

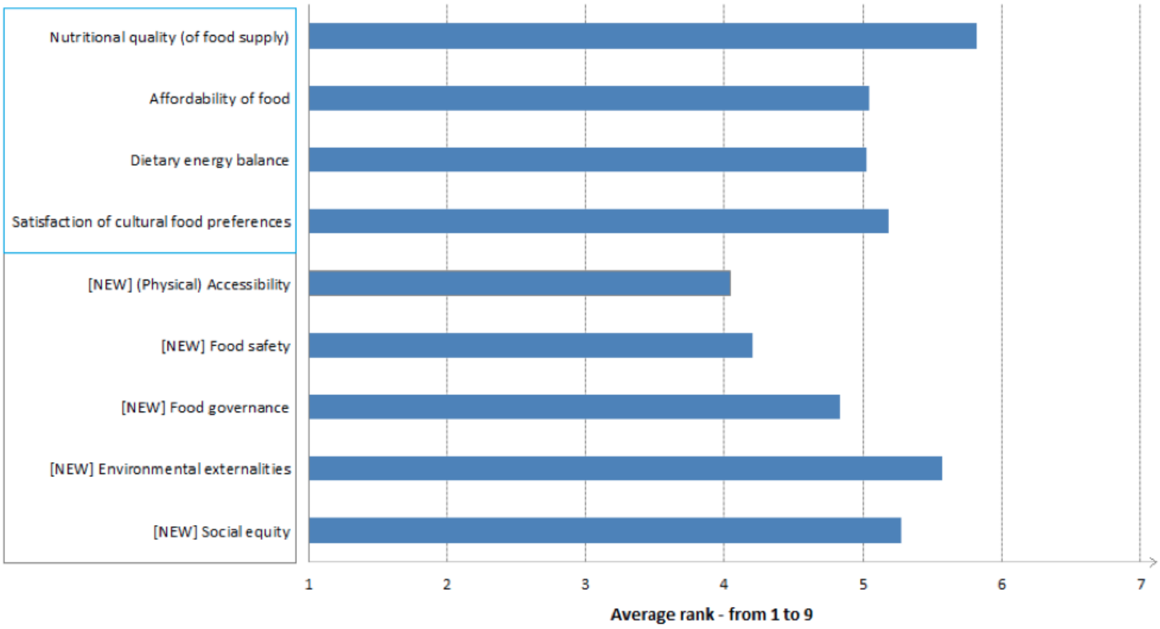

Figure 12 - Expert appraisal of the initial set of food and nutrition security issues and of the newly proposed ones

5.4 - Discussion

Discussion of the results

Discussion in terms of participation

The size of the expert group can vary depending on the complexity of the study and the management of the process. Generally the minimum number of participants required should imply at least four people (Thangaratinam and Redman, 2005), and there is not a maximum threshold, within the ability to ensure a sound and efficient management of the Delphi process. This is not only for the number of participants, but also the rate of participation in relation with the initially invited experts can sensitively vary. In a recent Delphi study - aimed at the identification of drivers, pressures, indicators of the environmental impacts on the Galapagos Islands (Benitez et al., 2014) - 42 participants were initially invited, only 10 (24%) actually participated in the first round and 5 responded to the third and final round. In another Delphi study - focused on finding an agreement on a definition of climate change adaptation (de Franca Doria et al., 2009) - 38 experts were invited and 23 (61%) effectively participated in the first round, and it was also specified that this number corresponded to 85% of those who initially accepted to participate (27). A third example of a Delphi study - on the identification of emerging food risk in the current food safety systems (Wentholt et al., 2012) - involved the invitation of 1931 experts, of whom only about 500 (22%) participated in the first round. Generally, as previously mentioned, a panel size within the range of 15–60 experts is considered appropriate for the application of the Delphi method (Hasson et al., 2000). In this Delphi study, the results obtained for the participation - both in absolute and percentage terms - largely fall within the standard recommendations for the implementation of the Delphi technique.

However, if on the one hand the number of experts is not always deemed fundamental, on the other hand balancing the panel may be considered compulsory and the validity of the Delphi study may be evaluated also on the basis of the quality of the experts (Powell, 2003). Often Delphi specialists recommend facilitators to end the process if the panel balance and quality are not sufficiently accurate (Benitez-Capistros et al., 2014). In this Delphi study the multidisciplinary composition of the Delphi panel was accurately monitored over the progression of the three rounds. In fact the rate of participation of each disciplinary group was maintained constant from the first round to the third one. The standard deviation - observed for the variations of the participation within each disciplinary group over the three rounds - ranges from a minimum degree of 0.004 for food technologist to a maximum degree of 0.016 for food system specialists. With regards to economist and nutritionist, both the most represented disciplinary groups, their rate of participation over the global panel participation progress constantly (see Table 6).

Table 6 - Participation rate and degree of variation of the Delphi disciplinary groups over the three rounds

DISCIPLINARY GROUP	INVITED	ROUND 1	ROUND 2	ROUND 3	ST DEV
Agronomy	13%	10%	8%	8%	0.012
Ecology / Environmental resources	16%	8%	8%	8%	0.004
Economics	23%	33%	31%	31%	0.015
Food security/policy	12%	12%	13%	14%	0.011
Food systems	7%	6%	5%	3%	0.016
Food tech	4%	2%	3%	3%	0.004
Nutrition	16%	22%	23%	22%	0.005
Statistics	2%	4%	5%	6%	0.008
Sustainability	7%	4%	5%	6%	0.008

Furthermore, the comparative analysis of the disciplinary composition rate - between the panel of the first round and the initial group of invited experts - shows that both economists and nutritionists increased their relative rate of participation. This might suggest that these groups are strongly interested in and sensitive to the general topic proposed in this "Metrics of Sustainable Diets and Food Systems" initiative. Also, as previously mentioned, both economists and nutritionists appear to tackle - in numerous scientific publications - the relevant issues related to sustainable diets and food systems through an holistic and multidimensional approach (Gussow & Clancy, 1986; Wilkins, 2005; Burlingame & Dernini, 2012; Guyomard et al., 2012; Johnston et al., 2014; MacDiarmid et al., 2012; Esnouf et al., 2013; Vieux et al., 2013; Burlingame, 2014; Masset et al., 2014). This was the main reason why they were mostly invited in the Delphi panel. Differently, the group of specialists in Ecology and Environmental resources, that was the second most invited category with nutritionists, may appear to be less sensitive to this initiative. In fact, from the starting point of the Delphi process, the results of the participation rate of this group fell largely below the attrition rate observed for the other groups. Although many of the experts invited from this group had long experience and considerable competence in vulnerability and resilience approaches and analysis of social-ecological systems framework, it is possible to suppose that they did not perceived to have common scientific interests and competences with a potential "Sustainable Diets" community. However first it is necessary to consider that this sample, for its size, imply limitations of statistical analysis and then the details on participation rate progression may not be representative. Second, this group is composed by several subgroups of scholars working on various fields related to ecology research and natural resources management, and this avoid strong generalizations about the reasons for their results of participation rate. Third, in Delphi studies it is key to take into account the role of the scientific network and contacts (cascade approach) for balancing the heterogeneity of the panel. Although the multidisciplinary aim of this study, the availability of professional contacts is not exempt from the risk of bias because of the specific scientific environment and the background where the initiative actually rose. Therefore - similarly as in several Delphi studies (Frewer et al., 2011 Check) - the panel composition is mainly turned towards two groups, economists and nutritionists, who bring important orientations and multidisciplinary diet-focused approaches. However, the involvement of several disciplines is key for further understanding and developing of systemic conceptual frameworks and assessment methods. Further analyses on participation rate by disciplines may rather belong to social, behavioral and cognitive science, and are not the main objective of this study.

Discussion on the indicators

According to Hasson et al. (2000) and de Franca Doria et al. (2009) consensus between 51% and 80% should be considered acceptable. Thus, in this Delphi study - as described in the results section - acceptable consensus on indicators was obtained on 18 interactions out of 24, which means an acceptable consensus on 75% of cases. Consensus on different indicators has been also categorized according to the threshold proposed by proposed by Keeney et al. (2010), namely majority (x > 50%), low (x > 50%), medium (x > 70%) and high (x > 80%) consensus. This shows that the Delphi technique is usually adapted and modified depending on contexts and goals of research.

In 6 interactions (25%) an acceptable consensus on one indicator was not reached, and in particular on 3 interactions a clear bipolarity was reported (two indicators above 35%). With regards to the dimensions where consensus on a single indicator was not achieved, it is still possible to find constructive elements for discussion. In fact, although the main goal of the indicators section is to identify a common consensus on one indicator, the Delphi technique still represents an opportunity to identify innovative solutions for unraveled problems. For some of the interactions that presented a manifest bipolarity of consensus, several experts proposed to integrate the two indicators into a composite one. This proposition could be potentially extended to all the interactions that presented bipolarity within the conceptual possibility of aggregation.

In Delphi studies stability of results is an essential criteria to assess the accuracy of the process. The main purpose of this study was to go through consensus for indicators that are qualitative nominal values, and there is no specific statistical test to measure the stability of responses between this kind of variables. Hence stability can be assessed through a descriptive statistical analysis that allow observing that, on average, 93% of the experts who selected the favorite indicator per dimension (at least 50%) in the second round confirmed their choices in the third round. This observation indicates that a certain degree of stability of the consensus has been achieved. Furthermore, as mentioned above 75% (18 out of 24) of dimensions reached, at least, a majority consensus (≥50%) on one indicator, and in all these cases the indicator which was the most chosen in the round 3, was been also the most chosen in the round 1 and in the round 2. This additional observation contributes also to demonstrate a certain degree of stability of consensus.

With respect to the selection of the indicators proposed to the experts, it is possible to identify one hypothesis behind each indicator. These hypotheses lie on the causal mechanism of vulnerability and resilience framework proposed. Thus, within a given interaction and belonging to one of the components of vulnerability (exposure, sensitivity, resilience) the hypothesis behind each indicator is formulated through the description of a functional relationship between indicator and vulnerability, as in a causal model similarly proposed by Gbetibouo et al. (2010). In table 7 these hypotheses are formulated for the indicators that reached low, medium and high consensus from the panel of experts in the third round, and presented within the related interactions, and with descriptions and details.

Table 7 - Analytical details of the formulation of the most selected indicators

Interaction[18]	Determinants of vulnerability	Component indicators	Description of the indicator	Hypothesized functional relationship between indicator and vulnerability	Unit	Data source	Sources	Consensus reached
WD / NQFS	*EXPOSURE*	Water Footprint of nutrient-dense foods [m3/kg]	Volume of freshwater appropriated to produce a product, taking into account the volumes of water consumed and polluted at the different steps of the supply chain. This indicator refers to a specific application of the Water Footprint to nutrient-dense food items. The selection of the relevant nutrient-dense foods is left open for now. The Nutrient density score (SAIN) is suggested to identify them (Darmon and Darmon, 2008).	The higher the appropriation of water to produce food items that respond to adequate nutritional requirements, the higher the vulnerability level [In this case the nutritional quality of the food supplied would be further exposed to water demanding production processes]	m3/kg	WFN	Authors' proposal (adapted from Water Footprint Network)	75% Medium
	SENSITIVITY	Intensity of use of actual water resources [%]	Percentage of TARWR (Total actual renewable water resources) that is used (sum of total withdrawals/abstraction).	The higher the intensity of appropriation of water, the higher the vulnerability level [In this case nutritional quality of the food supplied would me more sensitive to the effects of water withdrawal]	%	FAO	FAO	61% Low
	RESILIENCE	Irrigation Water Efficiency Index [%]	Product of assessed efficiency of irrigation water transport and distribution and theoretical plot irrigation efficiency.	The higher the efficiency of irrigation, the lower the vulnerability level [In this case, in order to insure an adequate nutritional quality of food supply, there would be further adaptive/transformative/coping capacities and opportunities for water management]	%		UNEP/MAP/Blue Plan	83% High
WD / AF	*EXPOSURE*	Water Footprint for an average diet [m3/yr]	Total volume of freshwater that is used to produce the goods consumed in a specific diet. It is the sum of direct and indirect water use of domestic and foreign water resources through domestic consumption.	The higher the appropriation of water to produce an average diet, the higher the vulnerability level. [In this case the ability to afford food usually consumed and acquired would be further exposed to an increasing water resource withdrawal]	m3/year	WFN	Water Footprint Network; Vanham et al., 2013	86% High
BL / NQFS	*EXPOSURE*	% of total acreage of top 5 varieties	Share of major varieties in total surface cultivated.	The higher the homogeneity of crop cultivated area, the higher the level of vulnerability [In this case the nutritional quality of the food provided would be further exposed to the increasing loss of biodiversity]	%	FAO	FAO, 2002	64% Low
	SENSITIVITY	Nutritional Functional Diversity	Measures the capacity of a given farm/system/ecosystem to provide the diversity of nutritional elements required. The nutritional FD metric is based on plant species composition on a farm/system/ecosystem and the nutritional composition of these plants. It is correlated to species richness.	The higher the capacity of a given agro-ecosystem to provide the diversity of nutritional elements required, the lower the level of vulnerability [in this case the nutritional quality of the food provided would be affected by an biodiversity loss to a lesser extent]	score [0-100]		Remans et al., 2011	83% High
	RESILIENCE	Crop Agrobiodiversity Factor	The CAF indicates the relationship between the number of major crops in a given area and the number of crops that are ecologically adapted to the prevailing management system.	The higher the ratio between the number of major crops and the number of crops that are ecologically adapted to the prevailing management system (in a given area), the higher the vulnerability level. [In this case there would be less resilience opportunities to insure an adequate nutritional quality of the food provided]	score [0-1]		Icrisat; Renkow, 2010	89% High
BL / SCFP	*SENSITIVITY*	% of diets locally produced	Share of diets that are locally produced (Authors' note: either in kcal or expenditure; a spatial criteria characterizing what is a local production needs to be defined).	The higher the share of diets that are locally produced, the higher the vulnerability level In this case there would be a manifest sensitivity of the satisfaction of food preferences face to a loss of the biodiversity in the food system]	%	-	CIHEAM/FAO, 2012	72% Medium

18 **WD** = Water Depletion ; **BL** = Biodiversity Loss ; **FPV** = Food Price Volatility ; **CFCP** = Changes in Food Consumption Patterns
NQFS = Nutritional Quality of Food Supply ; **AF** = Affordability of food ; **DEB** = Dietary Energy Balance ; **SCFP** = Satisfaction of Cultural Food Preferences

Interaction[19]	Determinants of vulnerability	Component indicators	Description of the indicator	Hypothesized functional relationship between indicator and vulnerability	Unit	Data source	Sources	Consensus reached
FPV / NQFS	*EXPOSURE*	% of nutrient intakes (Vit. A, Zn, I, Fe) from 10 most volatile foods	Percentage of total nutrient intakes derived from the 10 most volatile food commodities. One nutrient (Vit. A, Zn, I, Fe) needs to be selected or a composite indicator developed.	The higher the contribution in nutrient inputs to the household basket of the 10 foods presenting highest price variations, the higher the vulnerability level [The nutritional quality of the food supplied would be further exposed to fluctuations of food prices]	%	-	Authors' proposal	72% Medium
	RESILIENCE	Household Dietary Diversity Score	Measure of the number of unique foods or food groups consumed by household members over a given period. At household level, it is meant to proxy the average economic ability of a household to access a variety of foods.	The higher the number of unique foods or food groups consumed by household members over a given period, the lower the vulnerability level. [It would mean further opportunities for adapting to a vulnerability of the nutritional quality of the food supplied face to changing consumption models]	score		FANTA/FAO	92% High
FPV / AF	*EXPOSURE*	% of food household expenditure	Monetary value of acquired food, purchased and non purchased (including non-alcoholic and alcoholic beverages as well as food expenses on away from home consumption in bars, restaurants, food courts, work canteens, street vendors, etc.) over total household consumption expenditure (monetary value of acquired goods for consumption, food and non-food items, consumed by members of household).	The higher the share of a household expenditure for food, the higher the vulnerability level [In this case the ability of the household to afford food would be further exposed to fluctuations of food prices]	%	FAO	FAO	81% High
	SENSITIVITY	Sensitivity to price volatility	The score brings together the essential determinants of sensitivity to price volatility: price formation mechanisms, market power and price volatility upstream and downstream of the food industry, as well as the ability to pass on price variations downstream.	The higher the score of sensitivity of the agrofood sector to price fluctuations, the higher the vulnerability level.	score	-	Deloitte/PIPAME (France), 2012	86% High
CFCP / NQFS	*EXPOSURE*	Food Purchasing Power Index	Compares the evolution of the total cost of the food basket to the lowest monthly salary.	The higher the total cost of the food basket vis-a-vis the lowest monthly salary, the higher the vulnerability level. [In this case the nutritional quality of the food supplied would be further exposed to changing consumption models, since through complex non-linear system dynamics the food supply would follow the demand trends]	index		FAO; UN-ECOSOC, 1996	64% Low
	SENSITIVITY	Household Dietary Diversity Score	Measure of the number of unique foods or food groups consumed by household members over a given period. At household level, it is meant to proxy the average economic ability of a household to access a variety of foods.	The higher the number of unique foods or food groups consumed by household members over a given period, the lower the vulnerability level. [In this case the nutritional quality of the food supplied would be sensitive to changing consumption models to a lesser extent]	score		FANTA/FAO	83% High
CFCP / DEB	*SENSITIVITY*	Prevalence of underweight, overweight & obesity [%]	Percentage of population with a body mass index (BMI) of 25 kg/m2 or higher + percentage child and adult underweight	The higher the rate of obesity+overweight+underweight within a given population, the higher the vulnerability level. [In this case the equilibrium of energy intake would be further sensitive to changing consumption models]	%	WHO	WHO	69% Low

19 **WD** = Water Depletion ; **BL** = Biodiversity Loss ; **FPV** = Food Price Volatility ; **CFCP** = Changes in Food Consumption Patterns
NQFS = Nutritional Quality of Food Supply ; **AF** = Affordability of food ; **DEB** = Dietary Energy Balance ; **SCFP** = Satisfaction of Cultural Food Preferences

Even if an indicator list was provided, including a precise definition for each indicator and details about unit and bibliographical references, the hypotheses for each indicator were not integrated in the materials provided to the experts. The inclusion of this information in the indicator list might have helped participants for further understanding the framework and the selection process based on this causal model. However this would have also implied overloading participants with material to examine (it is reminded that experts were asked to make 24 choices within a list of 136 indicators) and it is acknowledged that an excessive burden of information expose a Delphi process to loss of participation and to the risk of early termination (Landeta, 2006). Also focus groups warned about this risk and adviced to keep limited amounts of information to provide to participants.

Furthermore, whether this selection of indicators provided acceptable results in terms of consensus and further perfectives for research, quantitative aspects still represents a limiting factor for several indicators in view of potential application. In fact data availability is usually one of the key criteria to consider in the selection of indicators and in the identification of composite indicators. However, in this Delphi study, the indicators that are not measured gain in interest and consensus. Indeed searching for appropriate metrics implies to go through what is desirable to measure and not which indicators are available (OECD, 2005). These findings might suggest that some of the indicators reaching consensus - that are not yet measured - are desirable to be measured. For instance, in table 7, the indicator "% of diets locally produced" (CIHEAM/FAO, 2012) - interaction BL/SCFP - reached a medium consensus (72%) as proxy variable for the sensitivity of the satisfaction of cultural food preference in a condition of biodiversity loss. Its hypothesis states that the higher the share of diets that are locally produced, the higher will be the vulnerability level. This hypothesis is based on the fact that in case of high level of diets that are produced locally, the fulfillment of the food preferences (strongly dependent on this local production) will likely be more impacted by an erosion of biodiversity in the agrofood system, since the performance of the local production may be closely related to the good conditions (high biodiversity) of the agrofood system. Experts expressed a medium consensus on this indicator instead of choosing one of the other indicators proposed in the sensitivity component of the same interaction (see Appendices X). Within these less-selected indicators some of them are quite easy to be measured. For instance the "Mediterranean Adequacy Index" (Alberti-Fidanza et al., 1999; Bach-Faig et al., 2011) or the "Consumer interest in ethical imports" (DEFRA, 2008) are two indicators that can be measured and are also widely acknowledged and well conceptually structured. Probably these two indicators were not favored since they are not enough appropriate in the specific context where they have been proposed. However this option can also be interpreted as a call for assessing factors that have not yet been measured, and for which there are still not available data. Hence it emerges one more reason for including further details in the indicator list; experts have been let choose freely for indicators without being influenced by the related availability of data. Is this the way "the best argument should win"? Are panelists making "some tacit knowledge explicit"? According to Tapio et al.'s (2009) ideal outcomes for a traditional Delphi, these are two essential questions that a Delphi study can help to answer.

Discussion on the drivers of change

The drivers of change proposed in the framework (Water Depletion, Biodiversity Loss, Food Price Volatility, Changes in Food Consumption Patterns) were not described - as well as the food and nutrition security issues - in the concept note of the technical brief that was provided to the experts. Drivers and issues were in fact considered enough widely acknowledged and understandable, also considering the level and the academic background of the experts invited. Moreover, during the exploratory focus groups it was suggested not to make the concept note overly heavy (namely "no more than 2 pages") to avoid attrition of participation. Finally, there were not critical remarks on the general meaning of these drivers and issues within the experts that really participated in the three Delphi rounds.

Relating to the appraisal of the drivers proposed, importance of biodiversity loss reached a weaker consensus among panelists; however it was the driver the most often ranked as “very important” as to its impact on the nutritional quality of food supply. While some experts considered that “changes in environmental resources will likely have impacts on nutritional quality of the food supply, (...) the primary driver of nutritional quality is not environmental. There is a substantial ‘buffer’ in the system that is associated with cultural/political/economic factors (...), for example, how food is processed and how the nutritional content of food is determined”. There seems to be a certain opposition between panelists on the importance of biodiversity. One expert wondered if “biodiversity [was] related with the number of foods favourable to nutrition? The selection of adequate plants or livestocks [sic], for example costless in water and with a good nutrients value, may be more efficient for sustainability”. On the contrary, other experts explicitly highlighted that “both domestic and wild biodiversity” and “intraspecific variation in nutrient content across varieties [are] extremely important” for nutritious food supply and healthy diets, an expert adding that “(...) plant variety breeding is going too far and in the wrong direction (...)”. An expert stressed the need to distinguish biodiversity and agrobiodiversity, and questioned whether “separate" indicators” were required. It has to be reported that Climate change, proposed by 5% of the respondents in the first round, has been highlighted again in the open ended questions as an important driver to consider per se, in addition to Water depletion and Biodiversity loss.

Discussion on the interactions

As mentioned in the results section, the categorization of drivers - likely to significantly impact food systems - presented in the 2nd EU-SCAR Foresight Exercise (2008) was used to group the drivers added by participants, through the analysis of the text.

Experts proposed a number of driver/issue interactions and the two most quoted per dimension were submitted for ranking importance. Hence, it was given the opportunity to propose new interactions, above those provided by the framework. This exercise is part of the goal of a Delphi study; it represents the possibility for the group to create a common understanding on wicked problems (Landeta, 2006). Once that the most quoted interactions have been identified and ranked by importance, they constitute eight additional typologies of impact of specific changes on the outcomes of the food systems. Also, they can represent eight more research hypotheses to explore the sustainability problems of the food systems. These newly emerged interactions are already acknowledged and established, at different extent and in different geographical contexts. The meaning of these interactions can be analyzed by providing general definitions of the interplay mechanisms.

Policy-actions is a driver of change that has been proposed by experts for impacting the affordability of food, the dietary energy balance, and the satisfaction of cultural food preferences. These interactions were mainly considered important by the Delphi panel. In this context, policy-actions comprehend the development and the implementation of governance tools and measures aiming at regulating the future growth of the food system through cross-sectoral gains including nutrition, health, trade, agriculture etc. With regards to the impact of policy actions on the affordability of food policy actions are generally identified to stabilize food prices and keep consumers more food- and nutrition-secure (Dube et al., 2012). Governments, civil society, media and intergovernmental organizations (for instance WHO, OECD) discuss on economic tools to address the affordability of food and change incentives for purchase, in different geographical contexts. (Hawkes et al., 2013). Through the regulation of prices, policy actions can have a strong impact on obesity and food related non-communicable diseases (Webb, 2010). For instance, several international bodies advocate economic and fiscal policies to endorse the consumption of healthier foods, ameliorate the nutritional quality of diets, and fund population health programmes (Lee et al., 2013). More broadly, in order to regulate the affordability of foods on the basis of their healthy attributes, food prices can be generally controlled by governments through a number of complex policy approaches. Pricing strategies, at a national level, can comprehend taxes on specific foods (soft drinks), exemption of value added tax for selected food groups (vegetables), and subsidies (agricultural and transport subsidies, voucher systems for high-risk groups) (Powell & Chalouppka, 2009; Sassi et al., 2009). With regards to the impact of policy actions on the dietary energy balance and the satisfaction of cultural food preference, it is likely that the direct impact affect first the affordability of food through regulation of prices.

Furthermore, experts proposed a wide range of drivers that is possible to identify in the broad set of Changing agrofood patterns. This driver relates to the dynamics that shape the structure of the food systems and the relationship within the food value-chain elements and stakeholders including the steps of production, trade, distribution, consumption, and waste (SCAR, 2008). The quality and concentration of markets and supply, and the power relationship between stakeholders within the value-chain are essential for achieving adequate food system outcomes. These factors also shape production capacity and patterns and have an impact on both the demand and production elements of food systems (Eakin, 2010). For instance, with regards to the typology of food production and the distribution structure, the increasing level of processed food sales it is a symptom of a double phenomenon. If on the one hand the food sector is able to meet and follow the food preferences of consumers and their purchasing power level through providing highly processed foods, on the other hand - since food consumption is increasingly turned towards this products (Regmi & Gehlhar, 2005) - marketing can strongly influence youngest food preferences putting these generations at risk of obesity, diabetes and food-related health problems (Nestle, 2006; Liverman and Kapadia, 2010). However technological innovations are largely applied for producing highly processed foods, that can have a negative impact on health and be, in the meantime, nutrient-poor.

Participants also suggested analyzing the impact of technological innovation on the nutritional quality of food supply. Technological innovation in the food system relates to advancements converging between bio, nano and information technologies. The productivity of agriculture will be improved through appropriate advanced technology and management techniques for resources and land. New technologies and techniques can lighten pressure on environmental and economic resources and help solving sustainability problems (SCAR, 2008). Thus, technological advances can be powerful drivers of change in term of resilience of the nutritional quality of the food provisioned (Misselhorn et al., 2010; Rolling et al., 2011).

Soil degradation is the only environmental driver, within the newly proposed drivers of change, that is analyzed in this section. It was suggested to explore the interaction between soil degradation and nutritional quality of food supply. Soil degradation affects human nutrition and health through reduction in the quantity and quality of food produced. Furthermore soil degradation implies pollution of soil and water with resultant impacts on human health. Hence, soil quality is considered as a key aspect of nutrition-sensitive agriculture, since it can help improving human nutrition (Keding et al., 2013).
Several experts also mentioned the interest for analyzing the potential impact of world population dynamics on dietary balance. However this interaction was mostly ranked as not important. However, urbanization and migration, two of the most representative population dynamics, are widely acknowledged to be responses to poverty and lack of employment. For instance, it is acknowledged that the impact on people's weight is consistent with an improved income level. In fact it has been observed that obesity increases as long as time passes after migration. This is similarly observed for diabetes prevalence (Diamond, 2003). In UK, US and Canada it has been observed that the children of immigrants may be at even higher risk of obesity and diabetes than their parents (Cairney and Ostbye, 1999; Kaplan et al., 2004; Candib, 2007). Thus, the reason why experts did not find important the impact of world population dynamics on dietary energy balance, may it refer to the geographical context of this Delphi study (France, Italy and Spain)? It has to be reported that France, Italy, and Spain fall within the 11 countries most inhabited by foreign-born population in the world (UN, 2014).
The reflection that emerged from the proposition and the appraisal of these new interactions show that there is no unique interpretation for any impact of a driver of change on a food and nutrition security impact. Often impacts can be either positive or negative. Thus, geographical- and context-specificity of food security issues remains key, vis-à-vis global or regional drivers of change. The contribution of inputs from experts through a Delphi study can significantly help identifying and understanding these contradictions.

Discussion on Food and nutrition security issues

Delphi participants were asked to propose further food and nutrition security issues - specific to the geographical context considered (Spain, France and Italy) - beyond the four issues presented in the initial framework. Respondents suggested 5 additional issues comprehending environmental externalities, social equity, physical accessibility, food safety, and food governance. In a following step experts assessed the all set of initial and newly proposed food and nutrition security issues.

Whether environmental and social welfare are two of the three main food system outcomes, which include food and nutrition security issues such as availability, access and utilization (Ericksen, 2008; Ingram et al., 2010), these two newly proposed issues - environmental and social - cannot be considered as conventional food and nutrition security issues, as usually encountered in the literature (Pangaribowo et al., 2013). Since the mid-80's, several scholars and international organizations have been proposing the concept of "sustainable food security" (WCED, 1987; Speth, 1993; WFS, 1996) or "sustainable food and nutrition security" today – as an enlarged concept of food and nutrition security considering environmental and social issues. Simultaneously, the term "sustainable food and nutrition security" has been used literally "to address the longer term, root causes of hunger and malnutrition" (Thompson et al., 2009) as a forward-looking concept characterizing the ability of food systems to sustain food and nutrition security. The connections between these two understandings are not clear. And further analysis and debate would be necessary to acknowledge, not only conceptually but also in practice, the introduction of environmental and social concerns into food and nutrition security issues and the related tradeoffs to adopt towards the sustainability goals.

Experts provided appraisal on the importance level of the global set of issues, and each disciplinary group may have provided different opinions. As mentioned above the sample does not allow a representative analysis between disciplinary groups. However - with regards to the most represented disciplinary groups (Economists and Nutritionists) - through a descriptive analysis, it is possible to perceive differences in the appraisal of the issues between these groups (see Table 8).

Table 8 - Appraisal of Food and Nutrition Security issues for Economists and Nutritionists' groups by Standard Deviation

FNS ISSUES	ECONOMISTS	NUTRITIONISTS
Nutritional quality (of food supply)	- 0.005	+ 0.013
Affordability of food	- 0.255	+ 0.087
Dietary energy balance	+ 0.109	- 0.038
Satisfaction of cultural food preferences	+ 0.145	- 0.075
Environmental externalities	+ 0.023	+ 0.094
Social equity	+ 0.081	+ 0.167
Accessibility	- 0.466	+ 0.203
Food safety	+ 0.190	- 0.167
Food governance	+ 0.127	- 0.284

On average, both groups contributed positively to the judgment of environmental and social issues and nutritionist appear to be more concerned by social equity. It is interesting to observe that each of the two groups seems to consider less important the issues that should be rather related to their own disciplinary background. For instance economists contribute negatively - on average - to the level of importance of the issues "affordability" and "accessibility" of food. Besides, nutritionists in comparison with other experts rank the importance of the issues "dietary energy balance", "food safety", and "satisfaction of cultural food preferences", under the average of the global panel. On the other hand nutritionists fostered rather "affordability" of food and "accessibility". The main discrepancies between the two groups are manifest with respect of the judgment for "accessibility", "food safety", and "food governance". Should we think nutritionists are more aware about the problems encountered by people living in areas that are considered "food deserts" and about all the related nutritional consequences? Do nutritionists have more information about the level of "food safety" in the geographical region considered and are enough confident with it? Are the economists more concerned by the economic risks of a safety-driven food crisis? Are nutritionists disappointed by the outcomes of previous food policies, or they are totally satisfied with them and think there is no need for further improving "governance"? Do the economists, instead, think that "food governance" can really contribute to food and nutrition security and further efforts are still necessary?

In interdisciplinary studies participants provide various skills to research efforts and it is essential to consider the values that different experts bring to the debate on food sustainability. This may help for exploring the food systems and for resolving some differences and making progress.

Methodological considerations

Suitability of the Delphi as a method

The Delphi method is a structured process for collecting knowledge from a group of experts by means of a series of questionnaires interspersed with controlled opinion feedback (Adler and Ziglio, 1996). In socio-ecological vulnerability assessment it is highly recommended to conduct expert judgment through the Delphi method, in order to ensure maximum objectivity (De Lange et al., 2010).

Expert opinion is often the only source of evidence when no data are available and when data are difficult to attain at affordable costs, time and due to given the complexity of environmental systems (Brooks et al., 2006; Burgman et al., 2011; Krueger et al., 2012; Vrana et al., 2012). In this research the Delphi method was applied because of its expert elicitation capabilities for complex systems and for the possibility to conduct a selection of indicators avoiding - through anonymity and control feedback - the problems of freely interacting groups such as the dominant individuals and the pressures to conform the majority of opinions. Proving individualized feedback from each round (Steyaert and Lisoir, 2005) allow informing participants on the majority of opinions and this can generate the modifications of the opinion of the minorities (Bolger and Wright, 2011). In this way consensus usually increases after each round (Orsi et al., 2011).

In this research, several elements might have contributed to achieve appropriate levels of participation and to generate consensus.

With regards to participation, this might have been encouraged because of having an institutional support (see Annexes 1 and 2) that guarantees the beneficial purpose for society and not an exclusively profit-seeking aim for the team running the study (Landeta, 2006). It was also mentioned that a Technical workshop, effectively held in Montpellier on November 2014, would have been organized at the end of the Delphi study and that participants would have been invited for further scientific discussion on the results of the elicitation process. Experts' collaboration might have been also positively influenced because of an appropriate setting of a plural team with a very good knowledge and understanding of the problems of the sustainability of the food systems; experts can feel to make an effective contribution to the theme being studied and this enhance their motivation to participate (Landeta, 2006). Allowance of co-nomination between colleagues might have also contributed to the latter point (Tapio, 2009). Furthermore, excessive attrition of participants has been likely avoided also thanks to the valuable recommendations for managing, motivating, feedback administrating obtained from the pilot application that was carried in two preliminary focus-groups (Jairath and Weinstein, 1994). Sending qualitative personalized feedback with comments, explanations, and suggestions from the experts might have helped to create a real interaction of the group and then keeping adequate participation (McKenna, 1994; Rowe et al., 2005). The utility of Internet approaches to Delphi in allowing for consulting large, geographically dispersed, expert communities (Frewer et al., 2011), was confirmed in this Delphi study. Also English as base language of the survey contributed to involve international and multidisciplinary participation; also, it does not seems that English has been a barrier for non-native English speakers. As last factor that might have contributed to Delphi participation is the double-edged sword of providing scientific contents and materials to participants. In fact, if on the one side it is recommended not to overload participants with materials, on the other side it is considered essential that expert be aware of the seriousness and relevance of the study (Landeta, 2006; McKenna, 1994). Related with this last point, the Delphi survey was structured to make each round less time-consuming than the previous one.

Before discussing the elements that might have contributed to generate consensus in this Delphi study it has to be reminded that consensus was globally reached on the set of indicators, drivers, issues and interactions, but for some indicators bipolarity and dissension emerged. The reasons of consensus (and of dissension) may lie on the several hypotheses and scientific arguments that led to the identification of the various research questions proposed, and on the experts' skills, background, and scientific perspective of sustainability of the food systems. However, there are general factors that have been reported as influencing the capacity of a group to reach consensus. In fact it is usually acknowledged that in Delphi group dynamics low status group members tend to 'go along with' the opinion of group members with a higher status and a group or a dominant group member tend to exert undue influence on the opinion of the group (Gupta and Clarke, 1996; Fein et al., 1997; van Zolingen and Klaassen, 2003, p. 318; Bolger and Wright, 2011). Moreover this factor further highlights the importance of the anonymity in Delphi studies as a main advantage that encourages experts to make statements on the basis of their personal knowledge (Snyder-Halpern, 2002).

Disadvantages of the Delphi technique have also been identified in literature and scholars have questioned the reliability, validity and credibility of this research methodology. Sackman (1975), for example, has noted that anonymity may lead to a lack of accountability because responses may not be traced back to the individual. Todays' Internet approaches allow tracking responses of participants, but for evident scientific and ethical reasons facilitators do not have to divulgate these information. In addition, it has been suggested that a consensus approach can lead to a diluted version of the best opinion and the result represents the 'lowest common denominator' (Powell, 2003, p. 378). It could be argued, however, that all approaches (for example, working groups, nominal groups) to gaining consensus run this risk. Others have argued that this approach is time- consuming, labour intensive and, therefore, expensive (Fitzsimmons and Fitzsimmons, 2001) although there is not agreement about this (Powell, 2003). A number of methodological issues arising in respect of Delphi have the capacity to threaten the credibility of the study and these include issues around panel expertise, number of rounds, questionnaire development, analysis and achievement of consensus (Hanafin, 2004).

Considerations of a Delphi application to a vulnerability and resilience indicator-approach

In this study the Delphi method has been applied to generate a common understanding, and a consensus, within a scientific research group to provide assessment tools for policy making on sustainable diets and food systems through a vulnerability and resilience framework. However there are a host of existing decision support tools that provide decision makers with evidence-based support on how to make decisions under risk and uncertainty (Keeney and Raiffa, 1993; Janssen, 1994; Zeckhauser et al., 1996). Meanwhile these approaches are not completely proved appropriate to manage the complex issues associated with global change (Webster, 2002; Wilby et al., 2002; Tol, 2003). Thus it is highly recommended consulting with experts and users in finding solutions for social-ecological systems' problems (Doria et al., 2009).

The Delphi technique offers a structured approach to collecting data in situations where the only available alternatives may be subjective approaches (Broomfield and Humphries, 2001). The main purpose of a Delphi application to the selection of indicators was to go beyond choosing indicators on the basis of the availability of data or through subjective and value judgment decisions of an individual (Linstone and Turoff, 1975). Other group approaches to reaching consensus have been found to be less appropriate to the development of sets of indicators. The main disadvantages with technique such as nominal groups (Carney et al., 1996), brain-storming (Hasson et al., 2000), focus groups (Morgan, 1997) and analytic hierarchy process (AHP) technique (Lai et al., 2002), and working groups is their risk of considering only the perceptions of the most outspoken or opinionated members of that group or only focusing on interesting or controversial elements (Fein et al., 1997). Similarly, the review of methods currently used to assess vulnerability, both in ecological studies as in social-ecological studies, reveals that assessments strongly depend on expert judgment. This can be seen as an advantage, e.g. by the use of state-of-the-art knowledge which can be adapted when new insights become available (De Lange et al., 2010). However, it can also be regarded as a disadvantage, because it is not clear how experts arrive to their judgments. This drawback can be overcome by using a standardized method, such as the Delphi method (Dalkey and Helmer, 1963).

The Delphi's participatory nature and the rigorous queries can enable close collaboration between researchers, with the aim of informing decision makers. This could enhance the scientific and policy relevance of the structured results of this application of the vulnerability and resilience framework. This adaptation of the vulnerability and resilience framework can represent an instrumental approach to be used with the Delphi method for similar future research on the assessment of the sustainability of diets and food systems. In the larger context of social-ecological systems frameworks this approach is often associated to shortcomings especially derived from a lack of agency in programmes and scarce communication from researchers to policy-makers (Foran et al., 2014). Starting from this Delphi study - its anonymity, iterative characteristics, and the statistical consensus - the pitfalls of the vulnerability and resilience approach applied to the sustainability of the food systems could be overcome by favoring a critical verifiable generation of group communication and information.

Use of Delphi method is not free from criticism. Keith (1996) proposes, for analyzing uncertainty issues in climate change, to focus on alternative ways in which policy-makers use science rather than eliciting expert to inform them. Testing the appropriateness of expert elicitation still remains a challenge (de Franca Doria et al., 2009).

The indicator approach that we applied is based on the vulnerability and resilience framework and uses a specific set or combination of indicators (proxy indicators) proposed to measure and explore the sustainability of diets and food systems. This approach is here applied at subnational level, but can be applied at any scale (e.g., household, county/district, national, system) through a context-specific selection of indicators. The major limitation of the indicator approach is its inability to capture the complex temporal and social dynamics of the various systems being measured. Differently from similar indicator-base approaches (Gbetibouo et al., 2010) the subjectivity in the selection of variables was avoided by applying the Delphi method. However further efforts will be needed to establish or not relative weights, to identify the availability of data at various scales or the need for further retrieval, to test or validate the different metrics (Luers et al. 2003), and to respect the essential criteria for validation indicators (OECD, 2008). However, the indicator approach is valuable for monitoring trends and exploring conceptual frameworks.

The indicator approach is the most common method adopted for quantifying vulnerability in the global change community (Gbetibouo et al., 2010). Leichenko and O'Brien (2002) highlighted the opportunity to capture the multi-dimensionality 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). The indicator approach is then used to develop a better understanding of the socio-economic and biophysical factors contributing to vulnerability

(Hebb and Mortsch 2007). This Delphi study represent also an opportunity to test in practice a vulnerability and resilience framework adapted from the Turner et al.'s (2003a) vulnerability/sustainability framework, and to improve the agency of the application through selecting indicators. This kind of framework is often considered to difficult and complex to apply (Turner et al., 2003b; Gbetibouo et al., 2010), however a system analysis still needs to take into account the non-linear mechanisms that regulate complex systems, and a multidisciplinary expert elicitation represent a way to tackle such a challenging issue.

5-5 Conclusions

The aim of this section of the thesis was to identify a consensus on a reduced set of indicators of exposure, sensitivity and resilience - within a larger set proposed to a panel of expert - to find solutions and tools for the assessment of sustainable diets and food systems. This goal was achieved through combined use of the participatory Delphi method and the vulnerability and resilience framework. The identification of these indicators, and the understanding of the drivers of change and of the food and nutrition security issues, would allow retrieving basic information to describe and measure the sustainability of the food systems face with global and regional socioeconomic and biophysical changes.

Following the guidelines for conducting Delphi research we obtained acceptable response and participation rates, and a balanced composition of the panel of experts from different disciplines. The Delphi study was conducted over three iterative rounds and high, medium, low and majority of consensus was progressively obtained on 75% of the interactions proposed. The drivers of change and food and nutrition security issues proposed in the framework were widely judged important, as well as the interactions presented. Furthermore participants contributed to enlarge the set of drivers and issues and the related new interactions. The panel highlighted the importance of a number of these new propositions of interactions that will generate further hypotheses and will be possible to consider for further research on problems related to the sustainability of the food systems through a vulnerability and resilience framework.

Further analysis of the socioeconomic and biophysical aspects of the sustainability of diets and food system could use or adapt the results of this Delphi study, not only by using the indicators, but also adapting the framework and the approach to other problems affecting the sustainability of the social-ecological systems at global, regional, national or local level. These efforts could be focused on support for decision-making.

This study has proved that the participatory approach – through the Delphi method – is a tool to gather opinions and forge group consensus. Delphi has demonstrated to be an efficient, versatile method capable of integrating knowledge of a panel of researchers. However, evaluation of the actual interest of the outputs of Delphi surveys into policies remains a topic that needs additional attention in order to demonstrate the actual effectiveness of the Delphi method.

The limits of this study, beyond the application of a vulnerability and resilience framework that is widely acknowledged and cited but also criticized, relate basically to the reduced number of interactions proposed, to the composition of the panel, and to the availability of the data for the indicators. However, the topics tackled by this framework can be opened to further research questions related to the sustainability of the food system. Furthermore, the preference for indicators that are not yet measured can encourage further retrieval of data for supporting decision-making. Although participation rate was acceptable and composition of the panel was constantly diversified all over the Delphi process, these aspects of a Delphi study can always be improved.

Chapter 6

General conclusions

This thesis aimed at developing a multidimensional framework, to identify metrics for assessing the sustainability of food systems and diets, applicable at a subregional level. Building on Social-Ecological Systems frameworks, the Mediterranean Latin Arc presents several socioeconomic and biophysical drivers of change making the food system vulnerable in its functions. A vulnerability/resilience approach was applied to analyze the main issues related to food and nutrition security. Formalizing the food system as a dynamic system, a model originates from this framework. Several causal models of vulnerability were identified, describing the interactions where drivers of change directly affect food and nutrition security outcomes, disentangling exposure, sensitivity, and resilience. This theoretical modeling exercise allowed the identification of a first suite of indicators. A reduced pool of metrics was then obtained through an expert-based elicitation process (Delphi Survey), moving beyond subjective evaluation and reaching consensus.

Hence, the general aim of this thesis was to analyze and explore the sustainability of the food system through identifying a set and a system of metrics at the Mediterranean level. This general aim involved three specific goals that have been identified through a sequential logic. The first specific goal was to develop a multidimensional framework to evaluate the sustainability of food systems and diets, applicable to countries of the Mediterranean region. At this stage it was essential to develop a conceptual framework to link concepts, methods, and metrics, for a multidimensional joint analysis and a broad understanding of food and nutrition security and food system sustainability. The second specific goal was to identify the main variables to formalize and operationalize the abstract and multidimensional concepts of sustainable food systems. It was key to identify the food system characteristics and fundamental systemic properties that make the food system capable of sustaining food and nutrition security outcomes. The third specific goal was to identify metrics for assessing the sustainability of food systems and diets, at a subregional level, combining a vulnerability and resilience framework and a Delphi elicitation process.

I. A conceptual hierarchical framework was identified for modeling the complex relationships between food and nutrition security and sustainability for the development of potential indicators of sustainable diets and food systems. Developing a conceptual multidimensional framework to explore the sustainability of the food systems implied adopting a broad sustainability approach that was reached through an extensive literature review on problems related to food and nutrition security ***(Chapter 1)***. The understanding of the food systems as a social-ecological system helped answering questions about the sustainability problems that affect the functions of the food system (Ericksen, 2008). Food and nutrition security is considered the principal outcome of any food system and is a multidimensional concept and relies on several properties of food systems, categorized as a range of activities (Ingram et al., 2010). Various elements of food systems are altered by, and actively impact, the socioeconomic and environmental conditions of the system across local, regional and global levels. These interactions are featured by, and bring with themselves high uncertainties, that can be explored through a vulnerability and resilience analysis, being vulnerability the propensity or predisposition of a system to be adversely affected (IPCC, 2014). Food systems can be vulnerable, and resilient, to a set of stressors (Adger, 2006) such as environmental pressures, socioeconomic 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). A food system is considered vulnerable when it fails in delivering one ore many of its intended outcomes, because of even small stresses that might bring to significant social-ecological consequences (Adger, 2006; Eakin, 2010). Fulfilling the food system outcomes remains challenging because of socioeconomic and biophysical stressors affecting the food system. Food systems are then considered social-ecological systems that comprise biophysical and social factors linked through feedback mechanisms (Ericksen, 2008). Theories of vulnerability and resilience, within the wider context of social-ecological system frameworks, proved helpful in several researches to understand the complex dynamics involving socioeconomic and biophysical aspects (especially in ecosystem management), to implement sustainable development strategies and research programs. However the operationalization of social-ecological systems frameworks remains challenging and still interests mainly researchers and, to a lesser extent, decision- and policy-makers. Foran et al. (2014) suggest that the reason why practitioners do not tend towards these approaches resides on their systemic characteristic, and then prefer apply more focused tools than too broad and systemic approaches. In the meantime this kind of frameworks are adaptable and then able to be integrated with other methodologies and assessment tools, in order to be more operational (Binder et al., 2013). Systemic understanding of the sustainability of the food systems can thus be further implemented also enlarging the research to multiple disciplines, multidimensional approaches, and integrated assessment and simulation tools to guide change ***(Chapter 2)***.

Hence, using the lens of a broad sustainability perspective, a multidimensional framework has been developed based on the vulnerability and resilience theories ***(Chapter 3)***. A causal-factors approach has been applied to study the sequential causal pathway defined by the relationship between exposure, sensitivity and resilience. Understanding the causal mechanisms that regulate the interactions between drivers of change and vulnerable food and nutrition security issues can help analyzing and interpreting available information, developing metrics, and anticipating new hazards and changes. The investigation on causes, effects and response to socioeconomic and biophysical changes can provide analytical tools to further understand the problems that affect the sustainability of the food system (Turner et al., 2003). This approach proved helpful for a general causal analysis of the vulnerability of the food system outcomes at a regional level, in the Mediterranean area. However it is still needed to clarify how the variables - belonging to exposure, sensitivity, and resilience - actually behave in a dynamic food system faced with several unattended socioeconomic and environmental drivers of change at multiple temporal and spatial scales.

II. Therefore the research targeted the identification of the main variables to formalize and operationalize the abstract and multidimensional concepts of sustainable food systems. A feedback-structured framework of the food system ***(Chapter 4)*** formalized eight causal models of vulnerability and resilience and identified intrinsic properties of the food system, shaping the interactions where external drivers of change directly affect food and nutrition security outcomes, at a subregional level. The previously mentioned causal pathway to vulnerability was then clarified. The challenge for social-ecological system frameworks analysis here is to identify the pathways leading to vulnerability, and the characteristics and opportunities ensuring resilience of the food system in a context of change. The identification of a causal pathway (adapted from Metzger and Schroeter, 2006; Fussel and Klein, 2006) allowed locating the role of the three variables, with exposure referring to relational variable and characterizing the relationship between the system and its environment. Hence exposure is the first point of contact between the stress or perturbation, and the system. The understanding of exposure as the first interface with a specific driver of change helps differentiating it from the sensitivity or resilience components, which might be influenced by other drivers of change. Building on the GECAFS food systems approach (Ericksen, 2008; Ingram et al., 2010), coupled with Turner et al.'s (2003) conceptualization of vulnerability, it is suggest a framework representing the model food systems' dynamics with feedback from outputs to inputs. Dynamic systems consider mainly two types of variables: endogenous and exogenous variables. In the case at hand, these variables are defined at the national or sub-national level. On the contrary, outcomes from the food system activities may however contribute to these external drivers. The three components of vulnerability – exposure, sensitivity and resilience – are the intrinsic features of the system that mediate the impact of the drivers of change on the food system's outcomes. These can be either state or control variables. This formalization of the food system dynamics allowed shaping eight causal models, in the geographical area of the Latin Arc, where the drivers of change and the food system outcomes of interest have been evaluated through the analysis of their potential causal relationships. These sets of characteristics are indicating how changes in water, biodiversity, food prices and food consumption patterns are transmitted through the food system, including the sequencing of events and the scale of interactions; how the food system is sensitive to these changes; and the adaptive capacity of the food system. This could lead to subsequent work to identify thresholds of change and to model quantitatively the interactions among stressors, attributes, and outcomes, to improve the general understanding of food system sustainability. It more importantly offers the elements that need to be assessed, i.e. the attributes that indicators can be measuring.

III. The identification of crucial interactions, within a complex food system, involving global and regional socioeconomic and biophysical drivers of change towards a set of context-specific food and nutrition security issues, and the identification of a causal model where variables are the characterizing properties of a formalized food system, allow the definition of a set of metrics for assessing the sustainability of the food systems ***(Chapter 5)***. The aim is to select metrics for assessing the sustainability of food systems and diets, at a subregional level, combining a vulnerability and resilience framework and a Delphi elicitation process. Part of the aim is also to involve participation of the scientific community in the selection of metrics. Whether several expert elicitation processes exist, Delphi studies are considered performing tools that provide a common understanding and consensus on unraveled problems, avoiding problems related to institutional or authority influence between the experts. The vulnerability and resilience framework was used as an analytical lens to provide a sequential list of sustainability indicators, while the Delphi method was used to determine which indicators are perceived as more relevant according to a selected group of participants. The Delphi study was conceived, and managed according to the recommendations of several scholars (Landeta, 2006; Fewer et al., 2011). In particular the Delphi process was structured to achieve the main aim of this research; a consensus on set of metric of sustainable diets and food systems. This involved also the selection of the invited researchers on the basis of their characteristics. A crucial factor was the selection of metrics for the initial set of metrics. Each indicator was identified following the hypotheses of the behavior of the variables underneath the mechanisms occurring in the interactions between a driver of change and a food and nutrition security issues. The results in terms of global response and participation rates and consensus on indicators were acceptable (Landeta, 2006). The results confirmed the validity of the conceptual framework and of the methodology applied. However strengths and weaknesses of this approach appear belonging to the same aspects. If on the one hand it happened that the panel selected metrics that are not measured with data - so there are not yet quantitative opportunities to test them - on the other hand this is also one of the purposes of the expert elicitation; to open the understanding and let experts freely propose innovative solutions. Then, there might be a call for measuring specific indicators that are not yet assessed. Furthermore, experts proposed also to enlarge the fields of the study through further drivers of change and food and nutrition security issues of the food system. There might be various perspectives for further research from these results, however, the Delphi method need to be managed in a way that could really be helpful for solutions, providing concrete and applicable outcomes, in order to offer decision-makers, stakeholders, and practitioners the possibility to fruitfully work throughout social-ecological systems frameworks for improving action on sustainable food systems.

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